

**The Effects of Bulkheading on Diamondback Terrapin Nesting
in Barnegat Bay, New Jersey**

A Thesis

Submitted to the Faculty

of

Drexel University

By

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in partial fulfillment of the

requirements for the degree

of

Doctor of Philosophy

September 2013

Acknowledgments

I consider myself incredibly fortunate to have arrived at this milestone in my academic career with the ‘problem’ of having too many people to thank. Truly, the completed puzzle of my dissertation would be imperfect without each and every integral piece – including Drexel staff, research advisors, Earthwatch volunteers, family and everyone in between. Thanks for helping me persevere and keeping a smile on my face.

The incredible guidance provided by my committee members over the past five years cannot be overstated. To my advisors, Dr. Harold Avery and Dr. James Spotila: Hal – Thank you for welcoming me onto the terrapin team with open arms. Your unwavering enthusiasm in the field and endless encouragement inspire me to never give up as an ecologist. Jim – Thank you for your constant support and guidance. I treasure your stories and am grateful for the friendship we have developed. Thanks to Dr. Michael O’Connor, I now consider myself a scientist with confidence in statistical analysis – perhaps the most academically valuable research tool for which I could ever ask. I can’t thank you enough, Mike. Dr. Walter Bien once gave me the most encouraging pep talk, when I was frustrated because I couldn’t recapture my outfitted terrapins. Thanks for reminding me to always stop and appreciate the beauty of nature around me, Walt. Thank you, Dr. Edward Standora for always reminding me to think of my research question first when trying to solve a logistical problem. Ed, without your guidance, I would not know many significant life skills regarding electronics, construction, or scientific design – Thank you. I am incredibly grateful to Dr. David Rostal for bestowing upon me his expertise in measuring herp hormones. Thank you for making our time together on the beaches in Barnegat and in the lab at Georgia Southern so memorable and fun, Dave.

Thank you to all of funders of this research, including the Betz Chair of Environmental Science at Drexel University, The Diamondback Terrapin Working Group, Sonotronics, Home Depot, Matthew Fidler at Protective Barrier Services/Yodock, and Dr. Tech Kah Lim with Drexel's Office of Graduate Studies. Thanks to Earthwatch Institute for their plentiful funding throughout my PhD, as well as for sending all the cool volunteers from around the world with which I had the pleasure to work. Protocols were approved by the Institutional Animal Care and Use Committee of Drexel University.

I am very grateful for all of the logistical support I received from near and far. At The Lighthouse Center, I love Pola Galie and Pat Augustine for being my moms away from home. Pola – Thanks for mending my wounds and always dropping everything to help. Pat – Thanks for getting up before dawn and making all my favorite dishes. A special thanks goes to those at Sedge Island for helping me keep track of the terrapins. Karen Leskie and Dr. Jim Merritt – Thanks for letting me bring my ugly barriers to Sedge and teach the school groups along the way. I've learned so much from both of you about how to be passionate environmental educators. Tony and Jackie Raniero – Thank you for your wonderful friendship and endless help with my project. I'm so appreciative of your support, and all that you do to keep Sedge protected and beautiful. This dissertation would have never been completed without the help of my wonderful friend, Dr. John Wnek. John – Thanks for always believing in me. You've taught me to always give people a chance, be trusting, persistently positive, and ever-encouraging – I can't thank you enough for these wonderful life lessons. Special thanks to Sue LaMarine and Dale White at Sonotronics for always helping me troubleshoot over the phone, and your delightful conversation.

Drexel undergraduates Janet Cai and Nisha Desai have my utmost gratitude for the many hours they volunteered towards helping me enter and analyze data. Thank you to all the field staff who pulled out their backs to help me move barriers, got up early to sit at the nesting beaches waiting for turtles, or sat on the boat all day listening for radio receptions: Bryan, Jason, Rachel, Lori P., John, Andy, Brian, Derek, Alanna, Erica, and especially Nicole. I can't thank five very special undergraduates enough for motivating me every day with their endless energy and hunger for field work – Thanks Spencer, Chris(py), Sam (Chunky), Lauren, and Anna – I couldn't have done it without you.

I am so appreciative of the wonderful friends I have made at Drexel. Thanks to Susan, Brenda, Kerin, Taz, and Kristen for all of the little and big things they do to help graduate students each day. Thank you to my fellow BGSA and DGWISE executive board members for always setting an example for me as motivated and outgoing people – I've had a blast working with you all. A special thanks to those graduate students who paved the way for me – Claire, Laurie, Gabi, Eugenia, Emily, Lucio, Bibi, and Victoria. Thanks to Josa, Kerry, Marissa, Sumona, Nina, Simara, and Shauna for being my buddies beyond biology – friends I could always count on for great advice and wonderful lunch breaks. Thanks to all of my eco-buddies – Noga, Deme, Kaitlin, Drew S., Anna, Dane, Ryan, Marilyn, Tom, Yuxiang, and Aliko – for your magnificent conversations about science and life. Shaya, Karen, Maggie, Laura, Jack, and Lori – Thanks for exploring the city limits together (often within beautiful gardens, local watering holes, or on our bikes) and for being reliable friends whom I could always count on. Jake, Samir, and Pat – Thanks for making me laugh when I was stressed, and always coming back from your worldly adventures so I was never without your benevolence for long. Abby – Thanks for

being my teammate and friend, especially in the field, where I'm always confident that anything can be accomplished as long as you are around. Kevin – Thanks for always listening. Always. Drew – We've been in this together from the get-go, and I can't thank you enough for being a truly generous friend in every capacity. Pearson – Your camaraderie from the first day I came to visit Drexel can not be overstated, and I want to thank you for all the beers, cheers, and everything in between. Thanks to Moxie & Gracie, Sasha & Griff, Jonas & Cody, Oscar & Gus, Loie & Oscar, Perdi & Pablo, and Hugo for always reminding me that nice long walks are the best way to enjoy a day.

Last but not least, I want to thank my family. Brian, Kelley, and Ava – Thanks for your understanding, support, love, and each bringing the party with you wherever you go. Gwen, Marta, and Jill – Thanks for knowing me better than I know myself and being the loving foundation for which I am eternally grateful. Eric – Thanks for being awesome and reminding me to enjoy life to its fullest. Lynette – Thanks for being encouraging and keeping me positive with each phone call, care package, and trip together (particularly shopping). I could not survive without you as my sister. Mom and Dad – You are the best role models that anyone could ask for. Thanks for teaching me to be thoughtful, compassionate, independent, loving, friendly, patient, honest, ambitious, creative, devoted, cheerful and strong through your example. Lastly, I want to thank the city of Philadelphia for being a wonderful home and continuing to provide my partner, Steve, and I with such wonderful memories together. Steve – Thanks for always being there for me, and lighting the fireworks. I am grateful to feel your limitless compassion and love each and every day.

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ABSTRACT**The Effects of Bulkheading on Diamondback Terrapin Nesting
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Julianne M. Winters

As human populations continue to increase, coastal development severely depletes the natural resources of America's estuaries. Barnegat Bay, New Jersey shows the highest rate of shoreline development of any mid-Atlantic estuary in the past 30 years. Hard erosion control walls, called bulkheading cover 45% of Barnegat Bay, impeding nesting diamondback terrapins (*Malaclemys terrapin*) from reaching high dune habitat. This dissertation's objective is to determine how diamondback terrapins behaviorally and physiologically respond to bulkheading and related anthropogenic activities while nesting. By monitoring two nesting beaches within Barnegat Bay, Conklin and Sedge Islands, I quantified the probability of terrapin nesting emergence simultaneous to environmental and anthropogenic factors. There was no significant effect of motorized boats, personal watercrafts, kayaks, or human presence on terrapin emergence. Instead, terrapins responded to environmental cues such as water (26 °C) and air (27.5° C) temperatures, time of day (13:30), and tidal stage (outgoing). To determine the effects of bulkheading on nesting terrapin movements I utilized biotelemetry to measure terrestrial and aquatic habitat use at artificial bulkheading. Terrapins showed variable, site-specific responses to bulkheading. At Conklin Island, terrapins encountering bulkheading travelled significantly further with more tortuous paths on land than females nesting at unobstructed beaches. At Sedge Island, however, terrapins spent significantly more time in the water at bulkheading instead of travelling more on land. I measured corticosterone

(CORT) and testosterone (T) secretion levels to determine the stress response in reproductive females from bulkheading. After handling, terrapin profiles of acute CORT increased significantly, approaching peak levels of 8 ng/ml. There were no significant increases in CORT or T due to bulkheading, however, indicating that barriers do not cause nesting terrapin stress. Over the reproductive season, T dropped significantly while CORT levels were maintained. My results suggest that diamondback terrapins lack behavioral and physiological responses to anthropogenic stressors at nesting beaches. To conserve shorelines for terrapins and other estuarine wildlife, sustainable development, accessible enhanced artificial nesting habitats, and human beach closures must be implemented. With the high rate of bulkheading construction in Barnegat Bay and nationwide, this research provides a novel approach to managing human-wildlife conflicts within America's estuaries.

CHAPTER 1: INTRODUCTION

Coastal Development and Bulkheading

Worldwide, approximately 4 billion people live within 60 km of the Earth's coastlines (Kennish, 2002). The human population is expected to increase at an exponential rate, approaching 6 billion individuals (the current global population) by the year 2025 in America alone (Kennish, 2002). In the United States, half of the original coastal habitat has been lost, primarily due to increased rates of human development and other activities (Kennish, 2001). There is a direct relationship between loss of natural habitat and the human population's shoreline development (Vitousek et al., 1997). Loss of habitat due to the increased coastal pressure poses a significant risk to biodiversity worldwide, as anthropogenic changes alter many natural processes (Small and Nicholls, 2003). In fact, the primary driving force in global biodiversity loss is due to human habitat alteration (Vitousek et al., 1997). Ultimately, increases in coastal human population create a domino effect – More development increases habitat loss, which leads to coastal fragmentation, and multiple genetic and demographic ramifications including species' reduced dispersal (Skole and Tucker, 1993), limited gene flow (Madsen et al., 1999; Sheridan et al., 2010), increased competition, reduced breeding opportunities (Madsen et al., 1999), and extinction probability (Vitousek et al., 1997). Thus, natural coastal habitat loss presents staggering conservation issues at multiple ecological levels.

Storms, tides, and weathering cause predictable responses from natural coastal habitat. Over time, natural shorelines will retreat landwards due to storm overwash and erosion (Davis et al., 2006). The human population developing upon these coastal systems will act predictably as well, attempting to halt shoreline erosion by installing

'hard' barriers such as bulkheading (Titus, 1991). These watershed retaining barriers act as further manipulation to the already existing development along a coastline, significantly altering the habitat and resources available (Jivoff, 2007). In estuaries, human development and bulkheading prevents new marsh from forming in the future, resulting in total marsh loss in some cases (Titus, 1991). While coastal marshes will already have difficulty keeping pace with the rapid rate of predicted sea level rise (Kennish, 2002), bulkheading will confound marsh development even further, preventing coastal expansion of sediment and grasses (Titus, 1991).

Barnegat Bay Estuary – An Ecosystem Impacted by Human Development

In relation to the rate of human population growth and development along the world's coastlines, Barnegat Bay Estuary, New Jersey is no exception. In fact, in many cases it's 67.5 km stretch of shoreline may be considered an extreme example of coastal development. Anthropogenic changes began within the region in the mid-17th century with the first European settlement, and have continued into the 21st century with Barnegat reporting a 450,000 census- which effectively doubles from June to August each year (BBNEP, 2001). Ironically, the same natural resources which are reduced due to human population numbers are the same features which attract a half a million visitors each year. Kayaking, canoeing, hiking, fishing, crabbing, personal watercraft use, boating, hunting, and beach visitation are among the many outdoor activities in which humans participate while in Barnegat Bay (BBNEP, 2001). In the past thirty years, Barnegat Bay Estuary has had the largest percentage of developmental increase compared to any other mid-Atlantic estuary (Jivoff, 2007). Based on imagery of shoreline

urbanization occurring within the last decade, this rate of development is showing no signs of slowing (Lanthrop and Haag, 2007). The rate of urban development within Barnegat Bay increased from 25% between 1995 and 2002 to 30% from 2002 -2006 (Lanthrop and Haag, 2007).

Estuaries are among the most productive ecosystems on the planet (Kennish, 2002). By supporting a high abundance and diversity of fish and invertebrates, estuaries exhibit extremely high primary and secondary productivity (Beck et al., 2001). Barnegat Bay Estuary is no exception, retaining an important role in New Jersey nearshore systems as a nutrient cyclers (Kennish et al., 2007), economically valuable fish nursery (Able, 2005), and major trophic system (Kennish and Lutz, 1984). The draw to visit this productive ecosystem accounts for the excessive rate of development within the bay, and thus dictates shoreline destruction and alteration. As of 2001, approximately 45% of Barnegat Bay's shoreline was bulkheaded (BBNEP, 2001). To indicate the actual rate of this bulkheading growth, 36% of the bay's natural shoreline construction has occurred within the past thirty years (Jivoff, 2007).

Effects of Bulkheading on Estuarine Wildlife

Many studies have been published documenting how bulkhead alters different habitat characteristics than the fringe marsh it replaces along estuary coastlines. These hard structures magnify wave reflection, which increases intertidal water depth, thus reducing the amount of benthic habitat receiving sunlight, which then eliminates benthic plants (Fear et al., 2004; Currin et al., 2009). The natural shoreline - an essential nursery habitat, juvenile fishes refuge, and home for many macrofauna organisms among shallow

seagrass beds – is now lost (Weis et al., 1998; Seitz et al., 2006). Further, toxic chemicals from the bulkheading's treated wood leach into the coastal substrate, leading to substantial loss of community structure (Weis et al., 1998). Both infaunal diversity and benthic organism density have been significantly reduced at bulkheading compared to natural marsh shoreline (Seitz et al., 2006). In fact, an entire shift in community structure from primary and secondary predators to smaller infauna prevalence has been observed at bulkheaded shoreline – results similar to what is seen in estuaries suffering from hypoxia stress (Long et al., 2011).

Although the negative impacts of bulkheading upon intertidal flora and fauna are clear, one direct result of bulkheading which has yet been quantified is the effects of limited access to terrestrial habitats from the water to wildlife. For this measure, a representative species, using both terrestrial and aquatic habitats during its life history, such as the diamondback terrapin, is necessary.

Model Species – The Diamondback Terrapin (*Malaclemys terrapin*)

General Species Ecology

The diamondback terrapin (*Malaclemys terrapin*) is an estuarine turtle species found along the U.S. Atlantic and Gulf coasts, from Massachusetts to western Texas (Ernst et al., 1994). Unique to brackish water salt marshes, this species is an influential member of the natural ecology of bay and marsh reservoir ecosystems. From March to September terrapins are active, found swimming in search of prey or mates, burrowing in mud, or basking on the marsh for thermoregulation (Davenport, 1992). Winter temperatures require terrapins to burrow deep into the soft mud of deeper bay waters for

brumation (Ultsch, 2006). A foraging generalist, terrapins may still exert a top-down food web control within its habitat, feeding on *Littoraria irrorata*, a periwinkle snail which grazes upon *Spartina sp.* (Silliman and Bertness, 2002). These grasses are essential stabilizers of benthic habitats, subsiding currents and helping to combat erosion within estuaries (Kennish et al., 2007). As major contributors to ecosystem function, long-living, and easily marked and identified, diamondback terrapins are exemplary species to measure the influence of human impacts upon an estuary (Gibbons et al., 2001).

Terrapin populations are in decline throughout the species' range, due to various human threats such as crab pot drownings, boat and road mortality, and the pet trade (Seigel and Gibbons, 1995; Gibbons et al., 2001; Dorcas et al., 2007; Cecala et al., 2009). Currently harvested as a fishery species in certain states (Brennessel, 2006), the conservation status of the diamondback terrapin is complicated and variable depending on the management techniques of a particular area. In NJ, the diamondback terrapin has been classified as a 'Species of Special Concern.' This is cited as any organism that warrants special attention because of evidence of decline, vulnerability to habitat deterioration, or any other modification that would result in the species becoming Threatened (NJDEP, 2008). Due to this special classification, the diamondback terrapin is a species which the New Jersey Fish and Wildlife Service would like to learn more about, in order to protect and prevent them from becoming Threatened (NJDEP 2008). For this reason, research examining terrapin habitat use and behavior relative to human bulkheading proves valuable for the management of the species.

The diamondback terrapin is a model vertebrate species for determining the effect of anthropogenic impacts on estuarine wildlife (Burger, 2002). As terrapins uniquely

utilize both aquatic and terrestrial habitats in their life history (Brennessel, 2006), they allow us to deduce the impact of bulkheading activities on the estuarine wildlife in Barnegat Bay. Two examples of terrapin terrestrial habitat use include basking and nesting. Considering both humans and terrapins utilize sandy high dune habitat - humans to build homes, and terrapins to nest (Burger and Montevecchi, 1975) - terrapin nesting behavior, versus basking, is directly impacted by coastal development and bulkheading. Thus, research towards better understanding diamondback terrapin nesting behavior in Barnegat Bay, both natural and in relation to bulkheading, will be particularly valuable towards better understanding the impact of human barriers upon estuarine wildlife.

Diamondback Terrapin Nesting Behavior

Variables dictating the nesting behaviors of diamondback terrapins vary throughout the species' range (Roosenburg, 1994). In New Jersey, terrapins select partially vegetated nesting sites along high sand dunes with low sloping inclines (Burger and Montevecchi, 1975; Wnek et al., 2013). Other variables affecting nest site selection include sand type and quality, tidal flux, vegetation occurrence, predation risk, and solar radiation (Feinberg and Burke, 2003).

Predation on eggs and hatchlings is a significant source of mortality in many terrapin populations (Burke et al., 2005). Foxes, raccoons, crows, and gulls have been reported as natural predators of terrapin nests (Burger, 1977; Palmer and Cordes, 1988). Proximate vegetation may act as effective cover from predators while females are on land nesting, but it may also provide camouflage for predators (Palmer and Cordes, 1988). Vegetative presence and its impact on nesting is complicated; proximal vegetation may

act as a beneficial substrate stabilizer, but also increases the probability of roots impeding digging and growing into eggs (Burger and Montevecchi, 1975).

As a species exhibiting temperature-dependent sex determination (Jeyasuria and Place, 1997), beach site temperature is another factor dictating nesting among terrapins. Indeed, daily high temperature was found to be positively correlated with the greatest terrapin nesting activity by Feinberg and Burke (2003). Estuaries exhibit highly variable tidal cycles, but in most instances terrapins have been found to nest most often during high tide (Burger and Montevecchi, 1975; Roosenburg, 1994; Feinberg and Burke, 2003). Crawl distance was reduced 50% at a study site in Little Egg Harbor, NJ during high tide, effectively reducing terrestrial time and energy allotment by a female (Burger and Montevecchi, 1975). Risk is decreased as well during a high tide, as exposure time to mortality is reduced regarding predation, desiccation, and potential thermal stress (Burger and Montevecchi, 1975).

Weather and time of day may also play a central role in emergence timing of nesting terrapins. Cloud cover is often cited as an important factor, although most reports are unable to make any correlation more specific than 25-75% cover, which is essentially half the time (Brennessel, 2006). Some studies report nesting between 1000 and 1500 hrs., almost exclusively (Roosenburg et al., 2003). Daylight nesting seems to be the norm among terrapin colonies (Montevecchi and Burger, 1975; Brennessel, 2006), with exception to reports of nocturnal nesting in Massachusetts (Auger and Giovannone, 1979) and occasionally in Barnegat Bay (Wnek, pers. comm.).

Overall, nesting ecology seems to be location-specific among terrapins, based on a report by Roosenburg in 1994 reviewing various aspects of terrapin nesting ecology and

its variation up and down the Atlantic shoreline. Overall, it is rule of thumb that an area uncovered during high tide (Roosenburg et al., 2003), with a gradual slope (Burger and Montevercchi, 1975), and slight vegetation (Feinberg and Burke, 2003) is a site with high potential for terrapin nesting within an Atlantic estuary.

Diamondback Terrapin Nesting Fidelity

With the significant number of variables determining a terrapin's nesting behaviors, it raises the question of how a terrapin finds their site of preference, and what occurs if this site is no longer accessible. One quantitative study of site fidelity occurred along a long marsh roadway in southern Barnegat Bay over a two year sampling period (Szerlag-Egger and McRobert, 2007). Within one season, approximately half of the nesting females selected sites of oviposition within 50 m of their previous clutches (Szerlag-Egger and McRobert, 2007). Between years, one third of individuals nested within 25 m of previous oviposition sites (Szerlag-Egger and McRobert, 2007). These data indicate that some turtles are fidelic to specific areas along a nesting beach. Areas more accessible from the water may have a higher density of terrapin nesting, increasing the probability of nesting in proximity to a past site naturally (Roosenburg et al., 2003). However, other variables dictating oviposition location have been studied as well.

When individuals return to reproduce in the place of their birth (or in the case of turtles, hatch), this is defined as natal philopatry, a behavior favored by natural selection where high fitness costs ensue in searching for new breeding sites (Lee et al., 2007). A recent study in Barnegat Bay found support for natal philopatry as a factor controlling nest site selection. Relatedness of nesting females was measured at various beaches within the Bay and then compared to distance between oviposition sites between

individuals (Sheridan et al., 2010). High and low relatedness was found between and among beaches, suggesting some site switching or bet-hedging behavior (Sheridan et al., 2010). Otherwise, there was significant relatedness between females nesting under 200m from each other, suggesting natal philopatry as a nesting trait in terrapins (Sheridan et al., 2010).

If site fidelity occurs, then the closure of a nesting site due to bulkheading may have significant outcomes on individual reproductive success and ultimate fitness. As habitat fragmentation increases within Barnegat Bay, the number of available nesting sites is becoming reduced (Sheridan et al., 2010). In a study by Baldwin et al., it was shown that reduced availability of nesting habitat for painted turtles (*Chrysemys picta*) increased individual female mortality, overall (2004). In addition, females travelled greater distances to find suitable habitat when nesting area was limited by human fragmentation (Baldwin et al., 2004). As high dune coastal habitats are often chosen by humans for development, bulkheading may be a threat to terrapin nesting by limiting access to their prime nesting areas in Barnegat Bay. With reduced available nesting habitats, terrapin energy and time allotted to nesting may increase. Much like painted turtles, distance travelled may also increase, making the probability of encountering sources of mortality more likely as well (Sheridan et al., 2010). Overall, nest site access is essential to maintaining terrapin reproductive success, and blocking these sites may decrease overall population fitness significantly (Sheridan et al., 2010).

Quantitative Tools to Measure Terrapin Nesting Behavior

Corticosterone and Testosterone as Measures of Terrapin Stress Response

External stressors (such as a blocked nesting beach) activate the hypothalamo-pituitary-adrenal (HPA) axis, resulting in marked elevation of glucocorticosteroid secretion to create the 'fight or flight' behavioral response (Wingfield et al., 1998). Considering many underlying daily-function hormones are also secreted through the HPA, high glucocorticoid secretion can subsequently alter the basal hormone levels within that organism (Valverde et al., 1999). In particular, this includes affecting the secretion of steroid hormones, sometimes with physiological results as severe as suppressing reproduction altogether (Moore and Jessop, 2003). In order to quantify the hormonal cascade related to acute stress and its various effects, endogenous rhythms of the HPA axis must be measured, as fluctuations in glucocorticoid secretion can obscure experimentally-induced stress responses. As basal hormone levels can be highly variable between species, it is essential that unique surveys of both basal and acutely secreted hormones exist for individual species (Rostal et al., 2001).

Although well documented within sea turtle literature (Rostal et al., 2001), the endocrinology of diamondback terrapins remains unknown. Corticosterone (CORT) levels are used as the primary indicator of stress in reptile species (Moore and Seigel, 2006). Surveys of female desert tortoise (Lance and Rostal, 2002) and leatherback sea turtle (Rostal et al., 2001) annual reproductive cycles indicate that testosterone (T) levels peak during follicle development at the beginning of their nesting cycle, making this hormone a likely reproductive indicator for terrapins. Thus, to best understand how terrapins physiologically respond to bulkheading at fidelic nesting beaches, both CORT and T hormone secretions must be monitored after exposure. T is a valuable indicator of

seasonal reproductive hormone fluctuations, and CORT can be used to determine if terrapins reached elevated stress levels due to barrier exposure.

Radio and Sonic Telemetry Monitoring of Terrapin Movement

Biotelemetry is an important emerging field within ecology, providing innovation and answers to continually developing questions regarding organism growth, development, movements, and energetics (Cooke et al., 2004). In relation to nesting, telemetry is an effective and valuable complement to the terrapin mark-recapture and genetic surveys being conducted in Barnegat Bay, NJ. Telemetry may provide important data regarding life history through fine-scale measures of movement, home range, and behavior (Block et al., 2005). Tracking individuals through electronic tagging and remote telemetry is a methodology for understanding aquatic movements of marine species, providing invaluable data for conservation wildlife management (Block et al., 2005; Shillinger et al., 2008). More specifically, passive telemetry is an important tool for monitoring and understanding movement of ecologically and economically valuable species (Sackett et al., 2007). Many aquatic turtle species (e.g., sea turtles) exhibit large home ranges which are monitored using satellite telemetry (Morreale et al., 1996). Conversely, diamondback terrapins exhibit fine-scale behaviors in restricted areas, thus more refined sonic techniques will be best (Roosenburg et al., 1999). Sonic or radio telemetry is ideal for investigating movements of species foraging, resting, and nesting over smaller spatial scales (Taquet et al., 2006).

Research Questions and Dissertation Structure

The goal of this dissertation is to determine the impacts of bulkheading on diamondback terrapin nesting in Barnegat Bay, New Jersey. Studies support that terrapins exhibit nest site and beach fidelity. When these sites are no longer available to diamondback terrapins due to bulkheading it is likely that their reproductive behaviors will shift. By quantifying changes in terrapin behaviors, movements, and stress levels we may determine the true impact of human disturbance upon terrapin nesting. The three focal research questions in this dissertation are:

1. What are the environmental triggers to diamondback terrapin nesting emergence, and how do anthropogenic activities impact this behavior?
2. Are nesting diamondback terrapins' aquatic and terrestrial movements altered due to bulkheading?
3. Do nesting diamondback terrapins exhibit a stress response when facing bulkheading at their fidelic nesting beach?

Answers to each of these questions can be found in their respective chapters within this dissertation. The main objective of chapter two was to determine the correlation between environmental conditions and anthropogenic activities on diamondback terrapin nesting emergence timing. Probability of diamondback terrapin emergence was calculated under optimal environmental conditions at various levels of human disturbance (i.e., motorized boats versus kayaks) to determine the effect of these activities proximal to nesting beaches. Chapter three focuses on quantifying the spatial and temporal alterations of female diamondback terrapins facing bulkheading at their fidelic nesting beaches. Radio and sonic telemetry was utilized to compare diamondback

terrapien movements between experimentally blocked (i.e., bulkheaded) and control beaches. In chapter four, acute corticosterone secretion levels show female diamondback terrapien's stress response to bulkheading. Testosterone cycles are presented throughout the nesting season, as well. Finally, chapter five summarizes the outcomes of this dissertation and discusses future research directions, detailing recommendations for wildlife managers towards best conserving diamondback terrapien nesting habitat in America's rapidly developing estuaries.

CHAPTER 2: ENVIRONMENTAL AND ANTHROPOGENIC TRIGGERS OF DIAMONDBACK TERRAPIN NESTING BEHAVIOR

Abstract

As human settlement and subsequent development along coastal estuaries continues to grow, wildlife are less likely to find suitable habitat without high levels of anthropogenic activities present. Barnegat Bay Estuary, New Jersey exhibits the highest coastal development rate of any United States mid-Atlantic estuary. The diamondback terrapin (*Malaclemys terrapin*) emerges onto the upland beach habitat within Barnegat Bay in order to nest – a behavior simultaneous to peak recreational activities throughout the bay and, in particular, along the coasts. To determine the effects of anthropogenic activities on this species' nesting emergence behavior, I monitored motorized boats, personal watercrafts (PWCs), humans walking or swimming nearby, and kayaks in relation to terrapin presence. I also recorded environmental variables including time of day, water and air temperature, cloud cover, wind speed, and tidal stage in relation to the timing of terrapin nesting emergence. I calculated the ratio of terrapin, anthropogenic, and abiotic presence and absence values across multiple models to determine probability of terrapin emergence in relation to each human and environmental factor. Time of day, air and water temperature, and tidal stage each were significant factors determining the probability of diamondback terrapin emergence. I found no relationship between any level of anthropogenic activity and terrapin emergence probability. Nesting females' lack of behavioral response to anthropogenic activities near their nesting site suggests that terrapins are either habituated or oblivious to actual threats within their surroundings. The diamondback terrapin's response to environmental factors while nesting allows

researchers to better predict when terrapins can be found near and on nesting beaches. As these weather conditions may be simultaneous to times of high human activity, wildlife managers can use my data to restrict recreational activities near coastal terrapin nesting habitats during peak nesting. With the increasing presence of humans along terrapin nesting habitats in Barnegat Bay, and nation-wide, this study acts as a novel approach to guiding management of the human-wildlife conflict within America's estuaries.

Introduction

Anthropogenic activities have been ever-present within marine ecosystems for thousands of years, being particularly impactful along coasts (Lotze, 2010), and steadily accelerating over the past century (Lotze et al., 2006). Ultimately, increased human populations along coasts generate a domino effect – subsequent development increases habitat loss, which leads to coastal fragmentation, causing multiple genetic and demographic ramifications including reduced breeding opportunities for many species (Madsen et al., 1999), and greater probability of extinction (Vitousek et al., 1997).

Shoreline development poses a particularly significant threat to aquatic, estuarine, and marine turtle species, as their nesting beaches are those most severely affected (Spotila and Paladino, 2004; Roe et al., 2013). The loss of their reproductive habitat, confounded by the subsequent intensification in proximal anthropogenic activities, can affect individual nesting females' behavior by limiting accessibility (Witherington et al., 2011) and altering their timing of nesting emergence (Moore and Seigel, 2006). Because many freshwater and estuarine turtle species are daytime nesters, they are particularly vulnerable to threats from motorized boats, personal watercrafts (PWCs), and general

human presence, as these activities are also more prominent during the day. Human presence startles nesting turtles back into the aquatic refuge (Moore and Seigel, 2006). Even in an un-altered, protected coastal habitat, triggers of turtle species' emergence to nest are still relatively unknown. Multiple environmental factors, such as time of day (Hirth, 1980; Swarth, 2004), tide and lunar cycle (Hirth, 1980; Gibbons, 1982; Reina et al., 2002; Swarth, 2004), temperature (Gibbons, 1982; Bowen et al., 2005; Pike, 2009), and general weather (Plummer, 1976; Gibbons, 1982; Bowen et al., 2005) are important, however, the effect of each factor is contingent on species and habitat. Thus, the combination of environmental and anthropogenic factors makes predicting nesting turtle's emergence a challenge. However, as shoreline development continues to encroach upon natal turtle nesting habitat, understanding how wildlife respond to these factors is becoming critical for management. Further, quantifying the impact of both anthropogenic and environmental variables on turtle nesting is crucial for designing accurate spatial conservation priorities (Moilanen et al., 2009; Mazor et al., 2013).

The diamondback terrapin (*Malaclemys terrapin*) is an estuarine turtle living in estuaries along the U.S. Atlantic and Gulf coasts, from Massachusetts to western Texas (Ernst et al., 1994). Environmental variables such as time of day, temperature, tidal stage, and weather, are consistently reported to dictate the nesting behaviors of the diamondback terrapin, however the actual values of each factor vary throughout the species' wide range (Roosenburg, 1994). For example, the greatest frequency of nesting terrapins occurs at daily high temperature in Jamaica Bay, New York (Feinberg and Burke, 2003), while terrapins are found to nest nocturnally in Massachusetts (Auger and Giovannone, 1979), when temperature is cool. Estuaries exhibit highly variable tidal

cycles, but terrapins nest most frequently during high tide in their northeast and mid-Atlantic range (Burger and Montevecchi, 1975; Roosenburg, 1994; Feinberg and Burke, 2003). Weather may also play a determining factor in time of emergence. Cloud cover is often cited as an important factor, although most reports are unable to find correlation more specific than 25-75% cover, which is essentially half the time (Brennessel, 2006).

Overall, nesting ecology seems to be location-specific among terrapins, based on a report by Roosenburg in 1994 reviewing various aspects of terrapin nesting ecology and their variation up and down the Atlantic shoreline. Generally, it is rule of thumb that an area uncovered during high tide (Roosenburg et al., 2003) with a gradual slope (Burger and Montevecchi, 1975), and slight vegetation (Feinberg and Burke, 2003) is a site with high potential for terrapin nesting, mid-day during amicable weather (Brennessel, 2006), within an Atlantic estuary.

While these observations of environmental factors dictating terrapin nesting timing are useful, they are exclusively based on observations of terrapin presence. More robust measures require a comparison of conditions when terrapins are present to those when terrapins are absent to be truly predictive of how this turtle, facing many human threats within its estuary, comes to emerge onto a nesting beach. Calculating the proportion of instances when terrapins are present or absent on a nesting beach compared to the presence or absence of an environmental or anthropogenic variable will allow us to determine terrapin responses to tidal stage, temperature, time of day, cloud cover, wind speed, motorized boats, PWCs, kayaks, and people.

The purpose of this study was to determine environmental and anthropogenic correlates to diamondback terrapin nesting emergence in Barnegat Bay, NJ. In the past

thirty years, Barnegat Bay Estuary has had the highest percentage of increase in development of any mid-Atlantic estuary (Jivoff, 2007), and its rate of shoreline development is not slowing (Lanthrop and Haag, 2007). By quantifying the proportion of terrapin presence/absence versus various environmental conditions I will be able to better predict when a terrapin is most likely to emerge to nest. Knowledge of environmental correlates to nesting will be a valuable control when determining how terrapin presence/absence is affected by anthropogenic activities. Thus, the predictions produced from my study will be useful to wildlife managers attempting to regulate when anthropogenic activities should be scheduled around terrapin nesting.

Materials and Methods

Site Selection and Terrapin Nesting Surveys

I monitored terrapin nesting at two sites in Barnegat Bay, New Jersey, U.S.A (39°47'N, 74°9'W): Sedge Island, one kilometer west of Island Beach State Park, and Conklin Island, within the Edwin B. Forsythe National Wildlife Refuge (Figure 2-1A). These sites were chosen based on their historically high levels of nesting activity. Wnek (2010) estimates a population size of 430 ± 23 terrapins at Sedge Island, with an annual mean of 90 female terrapins nesting in June to mid-July during 2002-2010. At Conklin Island, I inferred high nesting from previous depredation survey records – documenting over 100 nests per kilometer along its shoreline (Avery, unpublished data).

I chose two beaches with the highest nesting activity at each site based on Wnek (2010) and results of unpublished depredation surveys from 2006 to 2012. Beaches had similar terrapin accessibility (open beach), sediment type (sand), proximal water depth

(0.2-0.5m), beach length (Conklin 245-275 m, Sedge 65-90 m), and prominent vegetation (*Spartina spp.* and *Phragmites spp.*, Figure 2-1B).

I conducted six-hour surveys during the day, simultaneously at each of the two beaches on Sedge and Conklin Islands in July 2010 and June - July, 2011. Investigators sat inconspicuously among *Phragmites*, still allowing for unobstructed observation, and minimized their movements to reduce the potential of disturbing nesting terrapins. All observations were recorded within a 100 m radius of investigator locations, incorporating both terrapin and anthropogenic activities. Terrapin activity included time and location of emergence from water onto land. I documented 129 total emergence instances; 49 at Conklin, and 80 at Sedge. Anthropogenic activities included presence of motorized boats, personal water crafts (PWCs), kayakers, and humans (walking or swimming) in the aquatic or terrestrial habitat of the nesting beach. I recorded environmental conditions at the beginning, middle, and end of each survey day. Variables included water temperature (YSI 85, ± 0.1 °C), air temperature and wind speed (Kestrel 2000, ± 0.5 °C, ± 0.1 m/s), relative weather (overcast, rain, partly cloudy, mostly cloudy, or sunny), and tidal cycle (NOAA Tides & Currents).

Data Analysis

I consolidated survey periods into five minute intervals, with each interval documenting the presence or absence of a) turtles emerging, and b) anthropogenic activities, as well as the appropriate environmental conditions. If more than one turtle or anthropogenic activity occurred in a five minute period, they were maintained as one instance of “presence,” not multiple.

I examined each measure for normality and homogeneity of variances before statistical analyses. All tests were completed using R version 2.15.0 (The R Foundation for Statistical Computing), as described below.

Environmental Conditions Affecting Terrapin Emergence

I performed logistic regressions to determine relationships between time of day, water temperature, air temperature, maximum wind speed, cloud cover, and tidal stage and terrapin presence (i.e., emergence to nest). Each generalized linear model was set to a quadratic line of best fit, with the exception of tidal stage, which fit best to a 3rd-order (x^3) curve. Sites were tested together, as I had no indication that environmental conditions at Sedge and Conklin Islands would cause variation in terrapin emergence timing. Cloud cover was interpreted from investigator's designations of "Overcast" or "Rain" (100% cloud cover), "Mostly Cloudy (75% cloud cover), "Partly Cloudy" (25% cloud cover), or "Sunny" (0% cloud cover). Tidal stage was calculated for each five minute interval as time since last high tide. Values near -6 hrs and 6 hrs indicated approximately low tide, and those approaching 0 represented high tide. Thus, negative values indicated incoming tide, while positive values indicated outgoing tide. I conducted a chi-squared test for each model, determining for each if the environmental correlate versus probability of terrapin emergence was significantly different than a reduced model for the probability of terrapin emergence alone.

Anthropogenic Activities versus Terrapin Emergence

Utilizing the environmental results from 2.2.1, I developed anthropogenic activity models to determine if those factors had any additional effect on terrapin timing of

emergence. Thus, by incorporating the environmental correlates from 2.2.1 into my model, I tested if anthropogenic activities affected terrapin emergence only during optimal environmental conditions.

I performed chi-squared tests upon five models to determine if the simultaneous presence or absence of both anthropogenic activities and terrapins emergence were significantly different than what was expected. Each model was performed at Conklin and Sedge Islands independently, because of the difference in anthropogenic disturbance and relative protection from human activity at the two sites. Sedge Island supported an active education center for the previous 10 years, having up to 30 young students in the area of the nesting beaches daily. Nesting terrapins were handled repeatedly over that time period as well. Sedge Island was within a Marine Protection Zone, established in 2003, which forbid PWCs. Conklin Island, however, remained comparatively untouched and remote to human access, although it was within 1km of an active community boat launching ramp and navigation channel. Considering these site variations, terrapins may have habituated differently to the presence of motorized boats or PWCs and people at the two nesting beaches, thus I kept the sites separate in my analysis.

My first model considered all anthropogenic activities, whether motorized boats, PWCs, human presence, or kayaks, as equally weighted potential influences upon terrapin emergence timing. Taking into account that each anthropogenic activity may affect the terrapin's emergence probability differently, I tested four additional models in an attempt to determine the biologically relevant effect of humans in proximity to a nesting beach. Although non-reproductive terrapins do not behaviorally respond to motorized boats (Lester, 2012), motorized boats do create a considerable wake and a

large amount of noise within the range of a terrapin's hearing capacity. In addition, with a 11-15% motorized boat injury rate among Conklin and Sedge Island's populations (Lester, 2012), motorized boats are a real threat to nesting terrapins that are waiting in the water to emerge. Thus, my second test weighted motorized boats' impact to be three times that of the other anthropogenic activities. This model tested if a motorized boat's presence within a fifteen minute (instead of five) time interval affected terrapin emergence. Because PWCs were also an actual threat, and created noise and wake much like a motorized boat, my third model considered the presence of a motorized boat and/or a PWC within fifteen minutes and its effect on terrapin emergence. Because humans and kayaks were additional perceived threats to terrapins, but did not create a large amount of noise, direct injuries, or habitat modification, my fourth model did not weigh these impacts for more than their designated five minute interval. This model tested if a human and/or a kayak present within five minutes affected terrapin emergence. Finally, my last model tested if a motorized boat and/or a PWC present within fifteen minutes and/or a human and/or a kayak present within five minutes affected the timing of terrapins' emergences to nest.

Results

Environmental Conditions affecting Terrapin Emergence

Overall, of the environmental variables tested, temperature and tide had significant effects on the timing of terrapin nesting emergence at both Sedge and Conklin Islands (Table 2-1). Terrapin emergence to nest was significantly correlated with time of day. Terrapins were most likely to reach peak emergence probability (approximately 2%

in any five minute interval) around 13:30 on any given day during the nesting season (Figure 2-2). Temperature of the water along terrapin nesting beaches had a significant effect on terrapin emergence timing. Peak emergence occurred when water temperature was near 26.0 °C (Figure 2-3). Air temperature also had a significant effect on terrapin emergence, with the highest probability of emergence occurring near 27.5°C (Figure 2-4). There was no relationship between terrapin emergence and state of cloud cover or maximum wind speed. I observed two terrapins nesting in the rain. Tidal stage had a statistically significant effect on the probability of terrapin emergence. Terrapins were most likely to reach peak emergence probability approximately 2-4 h after high tide, when waters were in outgoing, ebb stages, approaching low tide (Figure 2-5).

Anthropogenic Activities versus Terrapin Emergence

At both Sedge and Conklin Islands, anthropogenic activities, overall, had no statistically significant effect on the probability of terrapins emerging to nest (Table 2-2). Motorized boats alone, with a weighted effect (within 15 minutes of emergence), did not have a statistically significant effect on timing of terrapin emergence at either site. Presence of motorized boats and PWCs, both with a weighted effect, did not affect terrapin emergence. Human and/or kayak presence did not affect timing of terrapin nesting emergence. Finally, all models combined, which included motorized boats and/or PWCs weighted and/or humans and/or kayaks unweighted (within 5 minutes of emergence), did not have a statistically significant effect on terrapin nesting emergence.

Discussion

Environmental Conditions affecting Terrapin Emergence

It is not surprising that water and air temperatures have significant effects on when female diamondback terrapins emerge to nest. In poikilotherms, such as the diamondback terrapin, internal temperatures depend upon external temperature (Gates, 2003). Thus, a nesting female terrapin's body temperature is very close to that of the water in which it is immersed adjacent to a beach, or the land upon which it emerges to nest. I found that terrapins were most likely to emerge for nesting at a water temperature of 26°C and an air temperature of 27.5°C, and that probability of emergence was greatest near these temperatures. While further studies are needed to fully understand the metabolic implications of these temperatures for terrapin nesting, they are important as guides for determining days when researchers and managers can expect a high probability of emergence within the nesting season. Terrapins in Jamaica Bay, New York nest at highest frequency at air temperatures near 25.4°C (Feinberg and Burke, 2003). Further south, nesting terrapins are most prevalent at air temperatures between 29 - 33°C in Florida (Seigel, 1980). Therefore, there may be a geographic gradient in temperature that maximizes terrapin nesting emergence. I expect that terrapins are acclimated to the temperatures that naturally occur in and around their nesting beaches in summer. Higher temperatures in the south are reflected in the higher temperatures that produce maximum nesting activity. My water temperature data are the first reported correlated to terrapin nesting. In other species, emergence frequency is highest in nesting painted turtle (*Chrysemys picta*) females at 21.5 °C in Illinois (Bowen et al., 2005). Along sea turtle nesting beaches in Florida, warmer sea surface temperatures (SST) trigger loggerheads

(*Caretta caretta*) emergence to nest, while SST has no effect on green turtle (*Chelonia mydas*) nesting (Pike, 2009).

My model suggests the highest probability of nesting around 13:30 EST, around mid-day in Barnegat Bay. In nearby Brigantine, New Jersey, terrapins nest between 7:00-19:00, although investigators do not report a correlation between time of day and terrapin nesting frequency (Burger and Montevecchi, 1975). Peak terrapin nesting activity occurs from 11:00-13:00 along the Patuxent River in Maryland (Roosenburg, 1994), and 9:00-10:00 in Barrington, Rhode Island (Goodwin, 1994). However, 45% of nesting terrapins nest at night on Cape Cod, Massachusetts (Auger and Giovannone, 1979). The difference between the results of these studies may be that the other studies are based solely on terrapin emergence frequency, and do not calculate the probability of emergence as in my results. It is unlikely that latitude is responsible for these differences since Rhode Island and Massachusetts are close to each other and the two studies in those location had quite different results. The possibility of site-specific local effects cannot be ruled out, but those may be confounded by methodological differences between studies.

Percent cloud cover did not influence terrapin nesting emergence in Barnegat Bay. Most other terrapin nesting surveys report similar results. For example, the highest frequency of terrapins nest in Jamaica Bay with 25-75% cloud cover, which encompasses most of the time and therefore is not very specific (Feinberg and Burke, 2003). Also, Burger and Montevecchi report their expectations to be low for terrapins emerging to nest on cloudy days (1975). Thus, cloud cover does not affect the probability of terrapin nesting emergence. Instead, any increased frequency related to lack of cloud cover is probably directly related to air temperature. Although I witnessed two terrapins emerging

during rain, that behavior is considered rare for terrapins (Burger and Montevecchi, 1975; Goodwin, 1994). Nevertheless, 15% of terrapins nest during rainy conditions in New York (Feinberg and Burke, 2003). Perhaps observations of terrapins nesting in the rain depend upon investigators being present on nesting beaches on rainy days.

Maximum wind speed did not affect probability of terrapin nesting emergence. No other study of freshwater or terrapin nesting reports on the effect of wind. I hypothesized that wind might affect nesting by making the water in the bay choppy and obscuring the beach to a terrapin coming to the surface in waves of $\frac{1}{2}$ to 1 m in height. That did not appear to be the case. The only reference to turtles nesting during windy conditions is the common observation that olive ridley (*Lepidochelys olivacea*) arribadas, or mass nesting events, often start on windy days. (Pritchard and Márquez, 1973).

Tidal stage did affect the probability of terrapin emergence. Specifically, my model suggested that terrapins were most likely to emerge during the outgoing tide, about 2-4 hours after high tide. This is unlike most terrapin nesting studies, which report the highest frequency of nesting to be during high tide (Burger and Montevecchi, 1975; Auger and Giovannone, 1979; Feinberg and Burke, 2003). Crawl distance was reduced 50% in Brigantine, New Jersey during high tide, effectively reducing terrestrial time and energy allotment by a female (Burger and Montevecchi, 1975). While I did not calculate variation in terrestrial distance relative to tide at Sedge and Conklin Islands, my results did not support previous reports of peak nesting during high tide that were based on emergence frequency. Perhaps the microtidal habitat within Barnegat Bay did not support enough change in water level at high tide to make that phase of the tide significantly better for nesting than the water level during the outgoing tide.

Anthropogenic Activities versus Terrapin Emergence

Despite multiple models, weighing various anthropogenic activities at their perceived and actual impact levels upon nesting female terrapins, I found no significant effect of motorized boats, PWCs, humans, kayaks, or the combination of these four activities upon probability of terrapin nesting emergence. While no other studies have quantified anthropogenic activities in relation to terrapin emergence, similar results have been found in *C. picta* in Illinois. Here, the frequency or density of recreational vehicles (RVs) on nesting habitat had no effect on probability of female turtles' emergence (Bowen and Janzen, 2008). In Illinois, as well as in my study in Barnegat Bay, there are two potential reasons for this lack of behavioral response; a) habituation, and b) inability to perceive human threats.

Habituation cannot be determined when only looking at one population (Whittaker and Knight, 1998). However, my study surveyed two different populations of nesting females, experiencing different levels of anthropogenic activities and found the same lack of behavioral response across nesting beaches. With the consistently high rate of coastal development within Barnegat Bay, New Jersey (Jivoff, 2007), and human influence beginning as early as the mid-17th century (BBNEP, 2001), it is possible that terrapins have been exposed to such a high level of anthropogenic activities that they no longer behaviorally respond. It may also be that female terrapins do not perceive humans on or near nesting beaches as a threat. Previous research on non-gravid, yet reproductive sized female terrapins in Barnegat Bay found no behavioral response to boat engine noise (Lester, 2012). In either case, my results further support the common claim that the

effects of anthropogenic activities upon wildlife behavior are species-specific, and are not able to be generalized (Whittaker and Knight, 1998; Bowen and Janzen, 2008).

Conservation Implications

While I am unable to determine whether habituation or inability to perceive human threats are the likely cause of the lack of effect of anthropogenic activity on terrapin nesting emergence, my results are informative to managers attempting to protect terrapin nesting habitat. Using my approach, researchers can now better predict optimal terrapin nesting activity based on environmental variables. In addition, managers can now temporally limit human activities near nesting beaches. Because actual threats, such as motorized boats and PWCs do not alter terrapin nesting emergence, these activities, in particular, should be restricted to areas a sufficient distance from known terrapin nesting beaches in Barnegat Bay, e.g., beyond 1 kilometer. This will sufficiently protect the large number of reproductively valuable female terrapins swimming near these beaches from June through mid-July.

Over the next 25 years, the ever-increasing human population along estuarine shorelines will create greater demands and pressures on estuarine systems (Kennish, 2002). My study shows environmental correlates that will allow humans to manage their coastal activities appropriately, without threatening diamondback terrapins. Through improved awareness of diamondback terrapin nesting behavior, we can better protect this species during one of its most vulnerable behaviors – nesting.

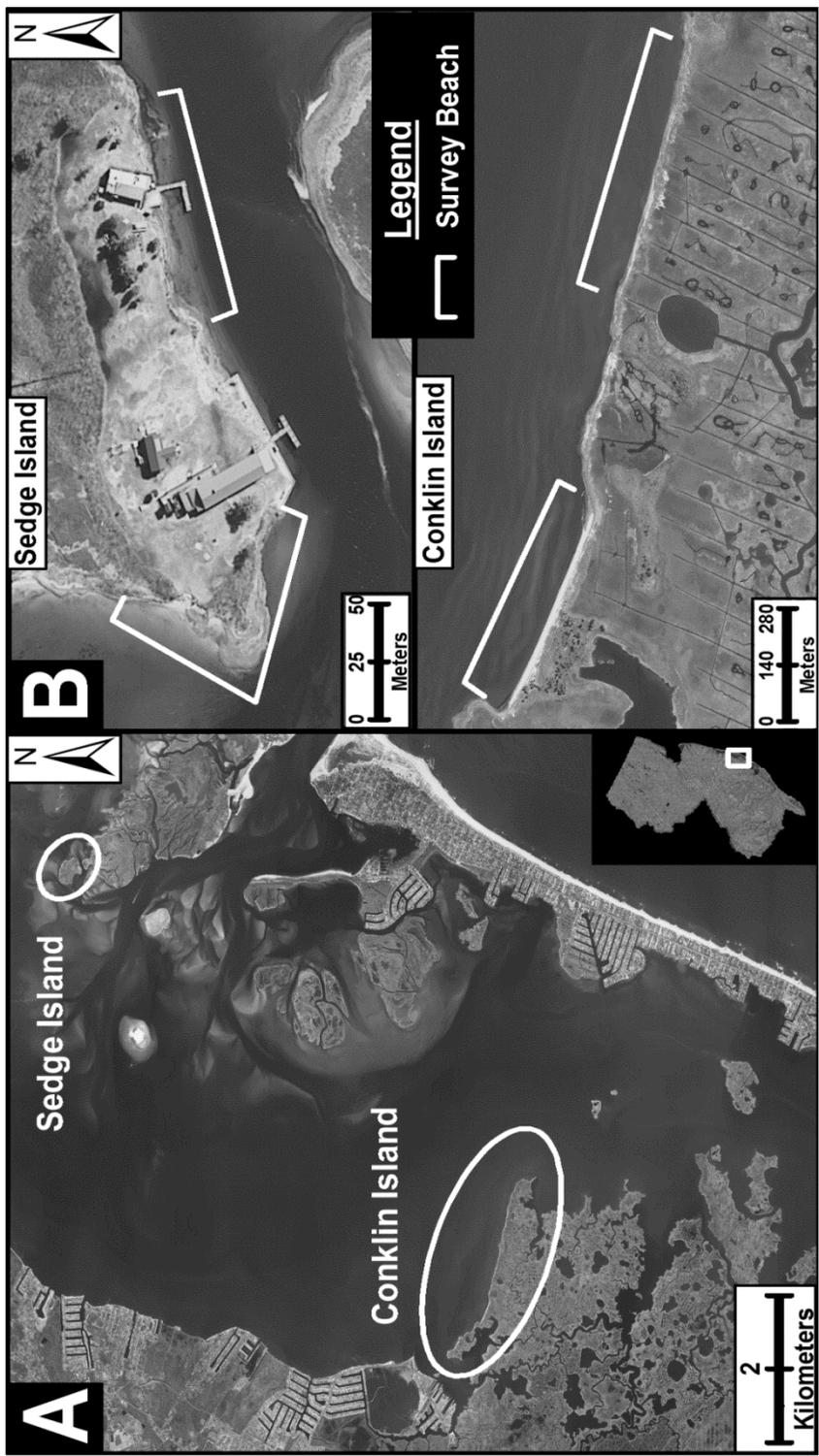


Figure 2-1. Barnegat Bay, NJ with terrapin nesting sites, Conklin and Sedge Islands (A), and (B) the two beaches at each site where terrapin nesting emergence were monitored in relation to environmental and anthropogenic activities.

Table 2-1. The effects of various environmental conditions on diamondback terrapin nesting emergence at Conklin and Sedge Islands in Barnegat Bay, NJ. Factors in italics indicate environmental conditions exhibiting a significant effect upon timing of terrapin emergence ($df = 1$).

Environmental Condition	χ^2	p	Predicted Peak Terrapin Emergence
<i>Time of Day (hr:min)</i>	22.6	<0.001	<i>13:30</i>
<i>Water Temperature (°C)</i>	14.9	<0.001	26.0
<i>Air Temperature (°C)</i>	19.8	<0.001	27.5
Cloud Cover (%)	5.3	0.07	NS
Maximum Wind Speed (km/hr)	0.6	0.73	NS
<i>Time from High Tide (hr:min)</i>	-4.7	0.03	<i>2:00-4:00 (Outgoing)</i>

Table 2-2. Anthropogenic models determining the effects of multiple weighted (by temporal proximity to emergence) activities on diamondback terrapin nesting emergence at Conklin and Sedge Islands in Barnegat Bay, NJ. There was no significant effect of any model upon terrapin emergence timing ($df = 1$).

Anthropogenic Activity	Conklin			Sedge		
	Time from Terrapin Emergence (min)	χ^2	p	χ^2	p	p
Boat, PWC, Kayak, and Human	5	-0.22462	0.6355	-1.5347	0.2154	0.2154
Boat	15	-0.53991	0.4625	-1.3164	0.2512	0.2512
Boat and PWC	15	-0.08557	0.7699	-1.2822	0.2575	0.2575
Human and/or Kayak	5	-0.96565	0.3258	-0.005918	0.9387	0.9387
Boat and/or PWC and/or Human and/or Kayak	15 (Boat&PWC)	-1.0268	0.3109	-0.000436	0.9834	0.9834
	5 (Human&Kayak)					

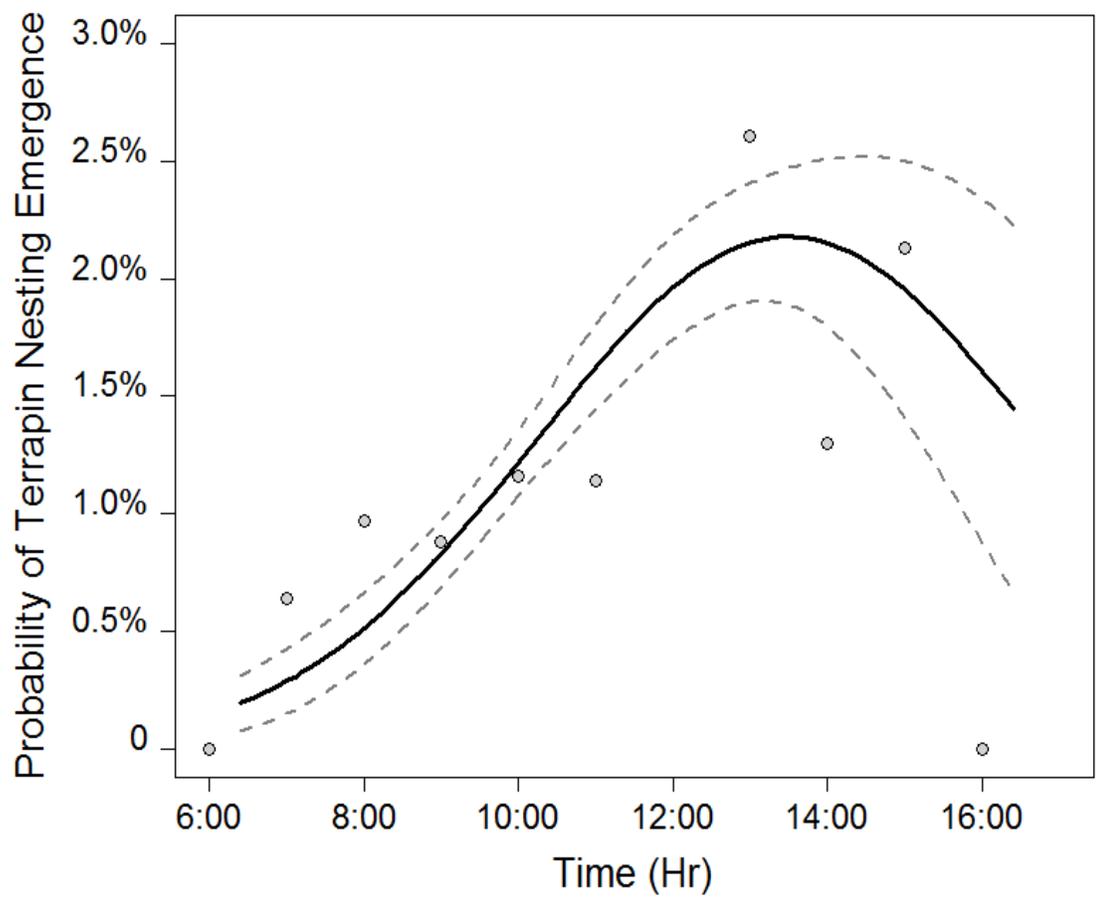


Figure 2-2. Probability of female terrapin emergence relative to time of day at Sedge and Conklin Islands. Black line represents the quadratic line of best fit, with 95% confidence intervals shown as gray dotted lines. Points document average emergence probability values. $df = 1, p < 0.001$.

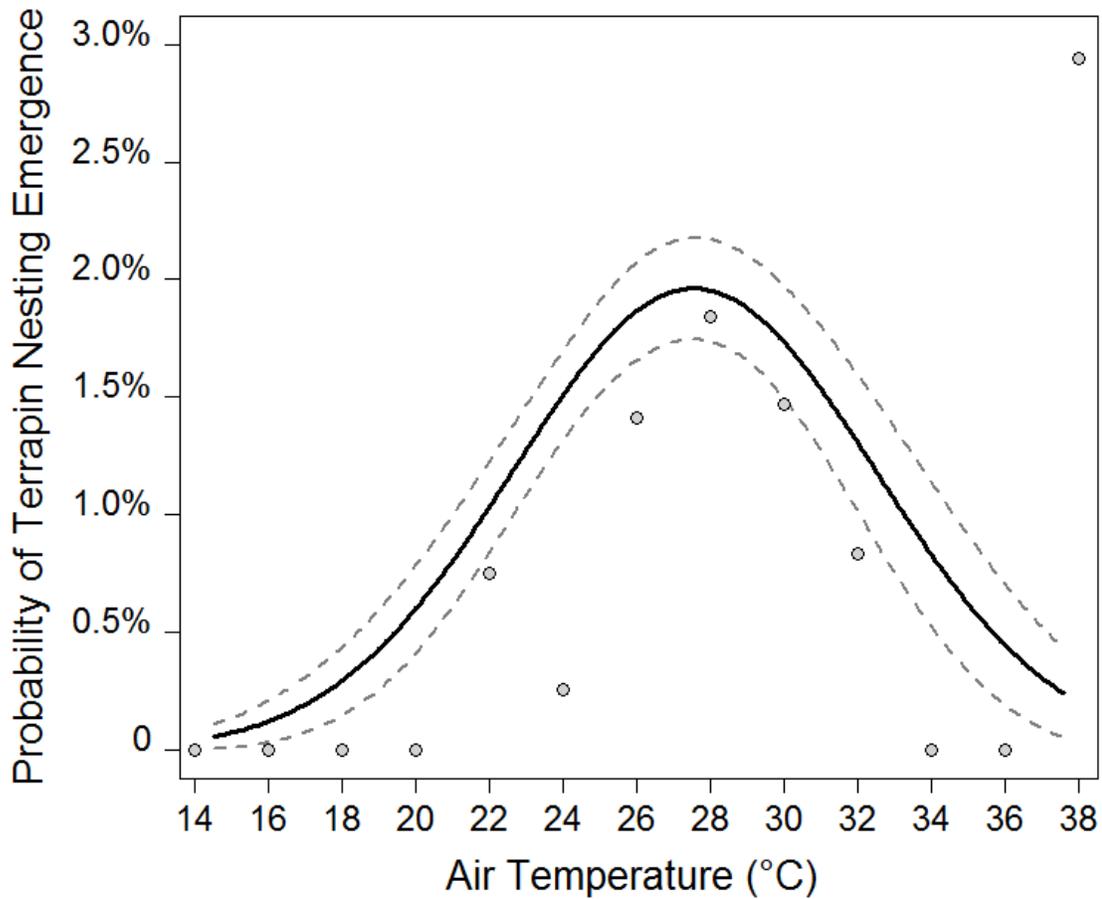


Figure 2-3. Probability of female terrapin emergence relative to air temperature at Sedge and Conklin Islands. Black line represents the quadratic line of best fit, with 95% confidence intervals shown as gray dotted lines. Points document average emergence probability values. $df = 1$, $p < 0.001$.

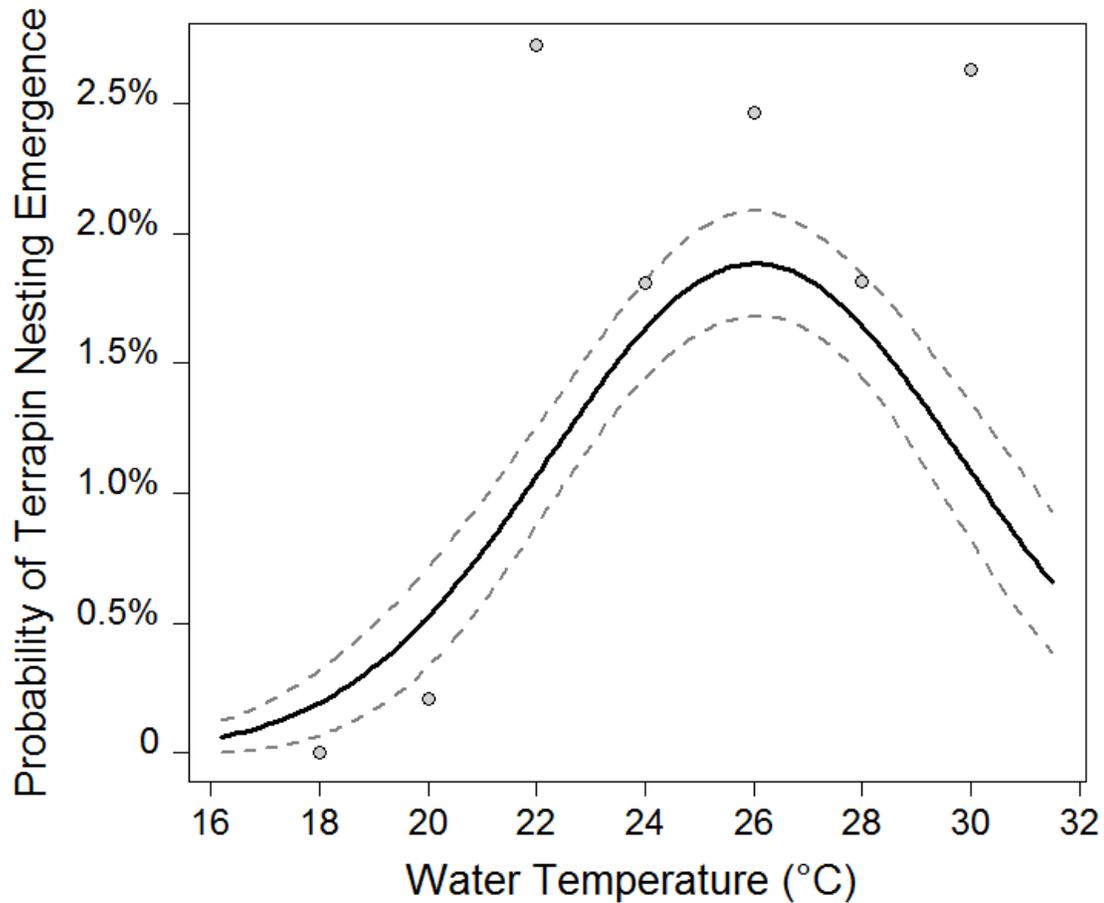


Figure 2-4. Probability of female terrapin emergence relative to water temperature outside nesting beaches at Sedge and Conklin Islands. Black line represents the quadratic line of best fit, with 95% confidence intervals shown as gray dotted lines. Points document average emergence probability values. $df = 1, p < 0.001$.

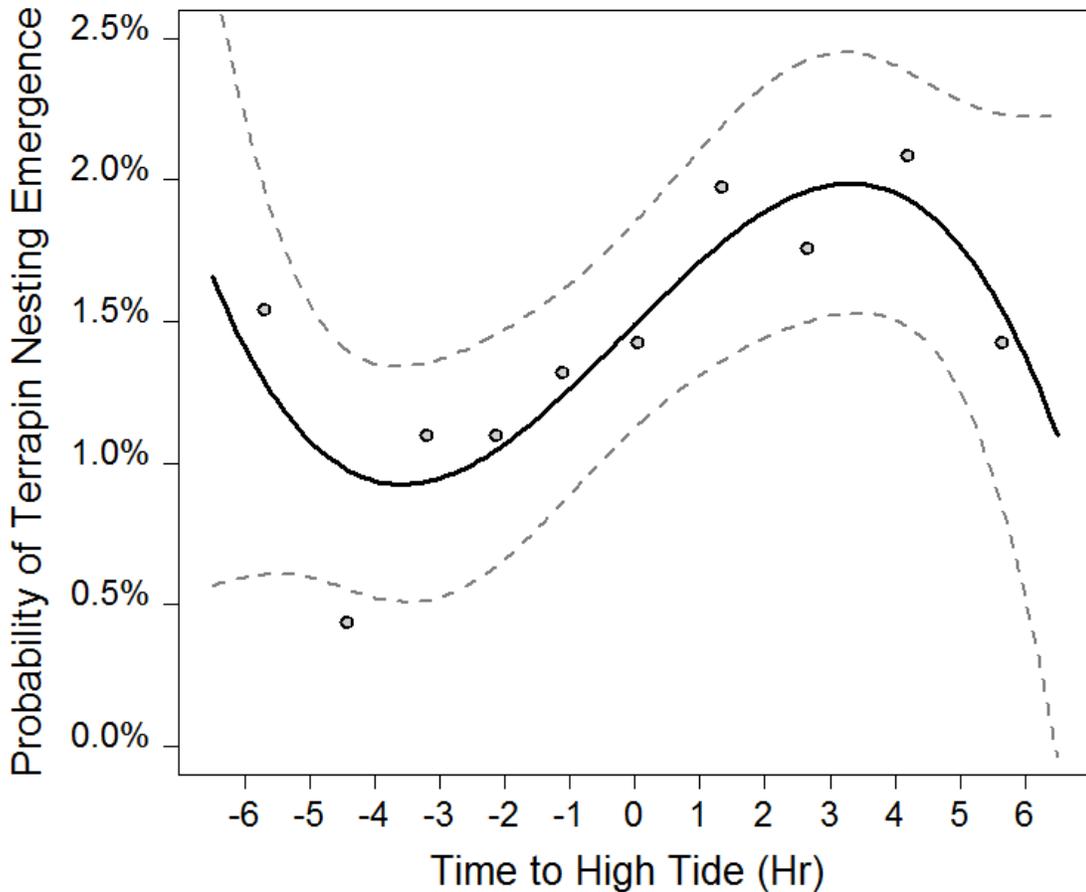


Figure 2-5. Probability of female terrapin emergence relative to tidal stage at Sedge and Conklin Islands. -6 and 6 both indicate approximately low tide, while 0 is high tide. Negative numbers are during incoming and positive are during outgoing tides. Black line represents the third-order line of best fit, with 95% confidence intervals shown as gray dotted lines. Points document average emergence probability values. $df = 1$, $p < 0.05$.

CHAPTER 3: ALTERED DIAMONDBACK TERRAPIN NESTING MOVEMENTS DEMONSTRATE THE EFFECTS OF BULKHEADING UPON ESTUARINE WILDLIFE

Abstract

Barnegat Bay, New Jersey exhibits the highest rate of shoreline development of any mid-Atlantic estuary in the United States. Along its shorelines, bulkheading has increased 30% over the past thirty years, potentially limiting upland access for wildlife. The diamondback terrapin (*Malaclemys terrapin*), a salt tolerant estuarine turtle, requires upland habitat for annual nesting. To determine the effects of bulkheading on terrapin nesting behavior I utilized biotelemetry to quantify terrestrial and aquatic movements in relation to artificial bulkheading at two fidelic nesting sites in Barnegat Bay. At one location, reproductive terrapins encountering bulkheading travelled significantly greater distances with more tortuous paths while nesting than females nesting at an unobstructed beach. At another location, however, terrapins spent significantly more time in the water adjacent to blocked nesting beaches, and did not travel greater distances on land due to bulkheading. Terrapins show variable, site-specific responses to bulkheading. I hypothesize that these significant spatial and temporal changes in reproductive behavior, both on land and in water, can reduce terrapin fitness and result in long-term population decline. My study provides a unique approach to quantifying the effects of barriers on nesting animals' behavior within North American estuaries, and is critical to understanding the impacts of bulkheading to other wildlife threatened by encroaching shoreline development.

Introduction

Approximately 4 billion people live within 60 km of the Earth's coastlines, representing only 10% of the Earth's surface (Kennish, 2002). This large concentration of shoreline settlement poses a major threat to coastal ecosystems worldwide (Hinrichsen, 1998). Due to the rapid rate of coastline development, habitat destruction is the second leading cause of global decline in estuaries (Lotze et al., 2006); a significant impact which is exemplified along the U.S. Atlantic coast (Kennish 2002). With the U.S. population reaching 6 billion individuals by the year 2025 (Kennish 2002), subsequent urbanization and development along Atlantic coastlines will exacerbate the strain on our estuaries' already compromised ecosystem services (Peterson and Lipcius, 2003). Mid-Atlantic estuaries, such as those in Delaware, Pennsylvania, and New Jersey, provide \$1.2 - \$10 billion in economic services per year (Costanza et al., 2006; Kauffman, 2011), with wetlands comprising the highest monetary value of any habitat type (Costanza et al., 2006). These ecologically-based economic appraisals reinforce conservation biologists' obligations to understand the direct and indirect effects of human development on estuarine habitats.

Over the past thirty years, Barnegat Bay Estuary, New Jersey, has lost the largest percentage of natural shoreline due to coastal development than any other mid-Atlantic estuary (Jivoff, 2007). Based on imagery of shoreline urbanization over the last decade, the rate of development facing this estuary shows no signs of slowing (Lanthrop and Haag, 2007). Coastal development leads to subsequent bulkheading, a vertical retaining wall which protects shorefront properties from waves and flooding. The consistent form of shoreline hardening in Barnegat Bay, bulkheading has replaced 36% of the natural

shoreline (Jivoff, 2007), posing a serious threat to estuarine wildlife at the individual, population, and community levels (Kennish 2002). Many studies have demonstrated the negative impacts of bulkheading on intertidal marsh species in the mid-Atlantic region, such as reduced nursery habitat for fishes (Able et al., 1998), decreased benthic infauna diversity and density (Peterson et al., 2000; Seitz et al., 2006), lowered vegetative biomass (Weis et al., 1998), and negative shifts in community structure (Seitz et al., 2006; Long et al., 2011). However, few studies exist that address the impacts of bulkheading on wildlife moving across aquatic and terrestrial shoreline ecotones.

I use the diamondback terrapin as a vertebrate model to determine the impacts of bulkheading on wildlife that utilize the aquatic-terrestrial interface. Terrapins exhibit two behaviors that require movement between water and land; basking along salt marsh edges for thermoregulation (Harden et al., 2007), and nesting on high-dune habitat (Burger and Montevecchi, 1975; Szerlag-Egger and McRobert, 2007). While basking location is not always predictable, nest site fidelity is commonly reported (Roosenburg, 1996; Butler et al., 2004; Szerlag-Egger and McRobert, 2007; Sheridan et al., 2010). In New Jersey, 40% of 300 reproductive females nesting along a roadside adjacent to salt marsh habitat ovideposit within 50 meters of their previous nesting site (Szerlag-Egger and McRobert, 2007). High genetic relatedness among terrapins nesting at the same site suggests that terrapins return to their natal beaches to nest (Sheridan et al., 2010). In addition to their nest site fidelity, terrapins greatly influence the community structure of an intertidal marshes, by top-down control of plant-grazing snail species, and indirect regulation of *Spartina*-rich salt marshes that are converted to ecologically dysfunctional mudflats in their absence (Silliman and Bertness, 2002). Further, terrapins are in decline throughout

their range (Gibbons et al., 2001; Harden et al., 2009), due to anthropogenic activities including watercraft and automobile traffic, crab trapping, and development upon marsh and nesting habitats (Cecala et al., 2009). Thus, understanding terrapin behavior relative to coastal development and bulkheading will provide invaluable insights towards conservation of an individual species as well as the threatened salt marsh ecosystem.

The purpose of this study is to determine the impacts of bulkheading on the nesting behavior of the diamondback terrapin. I use spatial and temporal measures that quantify behavioral changes in reproductive female terrapins, on land and in the water, in relation to bulkheading. I hypothesize that female terrapins encountering bulkheading while nesting will display greater changes in these terrestrial and aquatic measures than those encountering an unobstructed beach.

Materials and Methods

Site Selection and Experimental Manipulation

My study areas included two terrapin nesting sites in Barnegat Bay, New Jersey, U.S.A (39°47'N, 74°9'W): Sedge Island, one kilometer west of Island Beach State Park, and Conklin Island, within the Edwin B. Forsythe National Wildlife Refuge (Figure 3-1A). These sites were chosen based on their historically high levels of nesting activity. Wnek (2010) reported an annual mean of 90 female terrapins nesting at Sedge Island from 2002-2010 from June to mid-July, estimating a population size of 430 ± 23 individuals. At Conklin Island high nesting levels were inferred from depredation surveys, with over 100 nests counted per kilometer of shoreline during the nesting season.

I identified the two beaches with the highest nesting activity at each site (Conklin and Sedge Islands) based on Wnek (2010) and results of unpublished surveys from 2006 to 2012. Beaches at each site were selected based on similar sediment type (sand), terrapin accessibility (open beach), proximal water depth (0.2-0.5m), beach length (Conklin 245-275 m, Sedge 65-90 m), and prominent vegetation (*Spartina spp.* and *Phragmites spp.*). At one beach at each site I installed Yodock™ plastic construction barriers (The Yodock Wall Company INC., Model 2001M (Metropolitan), 182 x 45 x 81 cm) parallel to the vegetation line at the high water mark, central to the area of highest reported nesting emergence (Figure 3-2). This modeled bulkheading stretched for 25% of the beach length at each site (Conklin 67.7m, Sedge 20.1m). The second designated beach remained unobstructed and served as a ‘control’ beach (Figure 3-1B).

Terrapin Nesting Survey and Biotelemetry

I conducted daily six-hour surveys simultaneously at experimental and control beaches on Sedge and Conklin Islands in July 2010 and June - July, 2011. Investigators sat inconspicuously among *Phragmites*, allowing for unobstructed observation with minimal movements to reduce the potential of disturbing nesting terrapins. Both aquatic and terrestrial nesting behaviors were observed within a 100 m radius of investigator locations.

I collected nesting terrapins after one minute of attempted oviposition and brought them to the laboratory overnight. Here, they were measured and marked following procedures outlined by Sheridan et. al (2010). Females captured prior to oviposition were x-rayed to confirm that they were gravid and likely to return to nest, and then outfitted with both radio (Sirtrack, two stage VHF, 20g, 164-166 MHz) and acoustic (Sonotronics,

IBT-96-5, 3.2g, 40 kHz) transmitters on their carapace using PC-7 epoxy and monofilament tethers (Figure 3-3). I designed radio transmitters with a 45° spring antenna to ensure above-water exposure when the terrapin was at the surface breathing. I wrapped radio antennas in orange electrical tape to increase visibility in the water and on land. After outfitting, I re-released terrapins into the nearest water where they were originally captured.

Radio receptions facilitated all investigators' terrapin activity measures. When confirmed with a visual, these receptions were used to identify individual aquatic surfacing frequencies. Consistent receptions indicated a female emerging onto a nesting beach and facilitated calculations of terrestrial spatial displacement. Upon re-emergence of an outfitted terrapin to nest, I geospatially referenced point of emergence, path, and point of oviposition (Garmin, GPS 76 Marine Navigator, $\leq 5\text{m}$). I measured total path distance with a 100m transect tape to the nearest 1 cm. Returning females were not captured until completion of oviposition, at which point I collected the same spatial measures.

Passive acoustic telemetry documented time spent by outfitted terrapins in the aquatic habitat prior to emergence. Mounted to partially submerged 2.5 m PVC poles, Submersible Underwater Receivers (SUR, Sonotronics, SUR-2) passively recorded the gravid female's acoustic transmitter ID and time of reception. I installed SURs within 75 meters of each beach's shoreline (the calculated SUR range), thus ensuring that any terrapin with an acoustic transmitter in the aquatic habitat outside of a nesting beach would be recorded up until emergence onto land.

Aquatic and Terrestrial Measures

Terrestrial Spatial and Temporal Measures

I analyzed four measures of terrestrial movements to determine distance travelled by terrapins in relation to bulkheading. Three spatial measures were ‘Total Distance,’ ‘Net Displacement,’ and ‘Tortuosity,’ and one temporal measure was ‘Time on Land.’ For each measure, terrapins were considered experimental if they made contact and/or walked around the bulkhead upon emergence. I grouped all other terrapins nesting within the boundaries of the experimental beach, but not walking around the barriers as “avoid” terrapins. Females emerging to nest within the designated control beach habitat were deemed control terrapins. Due to insufficient sampling in 2010, terrestrial data were only included for 2011.

To calculate the distance for each spatial measure, I mapped GPS coordinates for an individual terrapin’s nesting attempt in ArcGIS v10.0 (ESRI, Redlands, USA) and then utilized the ‘pointdistance’ function in Geospatial Modeling Environment v0.7.1.0 (Spatial Ecology LLC, ©Dr. Hawthorne L. Beyer). Distances were compared to transect tape measurements for accuracy, confirming a ± 5 m confidence with geospatially referenced locations.

The first measure, Total Distance, included point of emergence, path points (or, fixes), and point of oviposition. Equivalent to the measure ‘path length,’ or L (Benhamou, 2004), Total Distance in my study represented the sum of distances between each location point (or, GPS coordinate). The second measure, Net Displacement or linear distance, was the straight-line distance between point of emergence and point of oviposition. Net Displacement represented the straight-line distance D between the initial

and final fixes of a random search path when measuring tortuosity (Claussen et al., 1997; Benhamou, 2004).

The third measure was the ratio between Total Distance and Net Displacement, or D/L (Benhamou, 2004). Because this index of straightness was a direct indicator of the tortuosity of an animal's path (Batschelet, 1981; Benhamou, 2004), I referred to this measure simply as Tortuosity. While fractal measures are also applicable to understanding tortuosity, the index of straightness I used is the ideal test for wildlife displacement studies (Claussen et al., 1997).

Considering barriers were different lengths at Sedge and Conklin Islands, I developed a 'Barrier Effect' model to test for any experimental design artifacts, such as terrapins travelling further at Conklin Island due to increased barrier length. For the model, I calculated total distance while in contact with the bulkhead for each experimental terrapin. The Barrier Effect model includes a one-way ANOVA to determine if Total Distance was significantly affected by the interaction factor of 'distance travelled along the barrier' and 'site.' If this interaction factor showed no significance I could then compare all terrestrial measures (i.e., Total Distance, Net Displacement and Tortuosity) between Conklin and Sedge Islands without concern for experimental design artifacts such as barrier length variation.

My final terrestrial measure, Time on Land, calculated travel time from point of emergence to point of oviposition. This temporal measure included total time on land, regardless of whether an individual completed oviposition, or not. Time on Land data were only collected at Sedge Island.

Aquatic Temporal Measures

I determined the amount of time terrapins spent in the aquatic habitat outside of bulkheaded and non-bulkheaded beaches using three measures, two related to observed surfacing frequency, and one related to acoustic SUR receptions.

For the first, ‘Individual Surfacing Frequency’ I calculated number of surfacing observations per identifiable terrapin. Considering I could not identify all terrapins, my second measure, ‘Total Surfacing Frequency,’ represented cumulative surfacing observations. In both measures, “experimental surfacing” included all surfacings observed in the aquatic habitat within 100m of the bulkheading. “Control surfacings” were those reported in the aquatic habitat within 100m of the designated control beach. Both measures included data from 2010 and 2011.

The measure, ‘SUR Presence’ calculated time in the aquatic habitat prior to nesting. I tabulated the number of SUR receptions for each terrapin outfitted with an acoustic transmitter, then calculating each individual’s ratio of time at the SUR using the following equation:

$$SUR\ Presence = \frac{Total\ Receptions}{Potential\ Receptions \left(\frac{Time\ in\ water(s)}{7} \right)}$$

Total Receptions is the number of SUR receptions from an individual terrapin. *Potential Receptions* is the time in water for each terrapin, counting the total seconds between terrapin release with an acoustic transmitter until recapture, then divided by 7 considering a SUR scans for transmissions approximately once every 7 seconds (Sonotronics, pers. comm.). Experimental receptions were considered those from the

experimental SUR and receptions relative to the control beach being those from the control SUR.

Data Analysis

I examined each measure for normality and homogeneity of variances before statistical analyses. All tests were completed using R version 2.15.0 (The R Foundation for Statistical Computing).

Due to lack of normalcy, I log-transformed Total Distance and Net Displacement prior to a one-way Analysis of Variance (ANOVA) for determining differences in distance between turtles in experimental, avoid, and control groups within and between Conklin and Sedge Islands. A Tukey's HSD test identified which groups were statistically significant at each site. Tortuosity is a purely descriptive measure (Batschelet, 1981), thus it did not require statistical analysis. I calculated Tortuosity as $1 - D/L$ to facilitate interpretation of the paths taken by terrapins. Therefore, Tortuosity values approaching 0 indicated a path closest to a straight line while those approaching 1 suggested a more tortuous, or, wavering path. For Time on Land, a Kruskal-Wallis one-way ANOVA was used to determine if terrapins exhibited significantly different terrestrial durations, while nesting, between groups.

Individual and Total Surfacing Frequency analyses were each modeled using a Poisson regression. Utilizing 2005 – 2008 Sedge Island data (Wnek 2010) I calculated terrapin nesting emergence frequency over the course of a season – an indicator of female presence in nesting beaches' proximal aquatic habitat. In addition to this probability factor, total survey hours and year were factors in my model, testing if surfacing varied at beach treatments within and between sites. The SUR Presence data from 2010 and 2011

were not significantly different (Student's t – test, $p = 0.142$), and hence combined, and ArcSine transformed. I used a Kruskal Wallis test to determine if there were statistically significant differences in SUR Presence at treatment beaches within and between sites.

Results

Results of all statistical tests are summarized both between experimental, avoid (where applicable) and control beaches at each site and between corresponding beaches at different sites (Table 3-1). These results show site-specific behavioral responses of terrapins to bulkheading: a significant terrestrial response at Conklin Island, and a significant aquatic response at Sedge Island.

Terrestrial Spatial and Temporal Measures

Total Distance was not significantly different between turtles in experimental, avoid, or control groups due to bulkheading at Sedge Island. However, at Conklin Island, nesting experimental terrapins traveled significantly greater distances when encountering bulkheading than avoid or control terrapins. Between sites, avoid terrapins at Sedge Island travelled significantly greater distances to nest than those at Conklin Island (Figure 3-4A).

Net Displacement of terrapins at Sedge Island was not significantly different between groups due to bulkheading. At Conklin Island, however, Net Displacement was significantly greater for nesting experimental terrapins than avoid terrapins. Terrapins within the same groups had similar Net Displacement between the two sites (Figure 3-4B).

At Sedge Island, Tortuosity levels did not differ for terrapins between all three groups. Terrapins exposed to bulkheading at Conklin Island, however had greater Tortuosity in their land movements than terrapins that avoided barriers or emerged on control beaches. Among sites, experimental terrapins' Tortuosity values were not different between Sedge and Conklin Islands (Figure 3-4C).

My Barrier Effect model indicated that differences in barrier length between sites (Conklin 67.7m, Sedge 20.1m), did not have any significant effect on terrapins' terrestrial movements. For example, a longer barrier did not affect the Total Distance travelled by terrapins at either Sedge or Conklin Islands (ANOVA: $F = 3.70$, $p = 0.14$), suggesting that terrestrial measure comparisons between sites were sound.

There were no significant differences in female terrapins' Time on Land between experimental, avoid, and control groups at Sedge Island.

Aquatic Temporal Measures

The Poisson regression for Individual Surfacing Frequency found that identifiable terrapins were surfacing more frequently in the aquatic habitat proximal to bulkheading than near an open beach at Sedge Island. At Conklin Island, however, bulkheading did not have a significant effect. There was no significant difference in Individual Surfacing Frequency between Sedge and Conklin Islands, at either experimental or control treatments in 2010 or 2011.

Total Surfacing Frequency was significantly greater among terrapins outside Sedge Island's experimental treatment than control. Conversely, there was no significant difference in total surfacing between treatments at Conklin Island. The interaction between site and treatment showed a significant effect in the model, indicating that the

magnitude of the effect of bulkheading was significantly greater on terrapins' total aquatic surfacing at Sedge Island versus Conklin Island. Total Surfacing Frequency was significantly different between sites at both experimental and control treatments in 2011, but there was no significant difference between sites in 2010 (Figure 3-5A).

Terrapin SUR Presence was significantly greater at experimental versus control treatments at Sedge Island, suggesting that terrapins spent more time in the aquatic habitat proximal to a bulkheaded nesting beach than an un-blocked beach. Alternatively, there was no significant difference in SUR Presence between treatment beaches on Conklin Island. Overall, SUR Presence was significantly higher among terrapins nesting at Sedge Island versus Conklin Island, at both experimental and control beaches (Figure 3-5B).

Discussion

Terrestrial Spatial and Temporal Measures

Overall, terrapins encountering bulkheading did not travel significantly greater distances, or spend more time on land in order to nest at Sedge Island. At Conklin Island, however, nesting terrapins travelled significantly further on land due to bulkheading. Similarly, painted turtles nesting near roads travelled significantly greater distances to find appropriate nesting habitat than those in less developed areas (Baldwin et al., 2004). Therefore, those travelling further to nest were much more vulnerable to upland dangers (Baldwin et al., 2004). Whether nesting along a road or in proximity to bulkheading, increased terrestrial distances by nesting turtles may affect adult female survivorship. For terrapins, mammalian predators such as raccoons are a substantial threat to nesting

individuals (Feinberg and Burke, 2003). Siegel (1980) found up to 86% of depredated terrapins were those of reproductive females. Overall, nesting terrapins travelling greater distances due to bulkheading at Conklin Island suggests increased probability of predation and lower reproductive female survivorship – a serious concern when considering population viability for this already declining species.

My findings of increased terrestrial nesting displacement at Conklin Island differ from a similar survey of nesting turtle response to artificial bulkheading. Witherington et al. (2011) found loggerheads encountering a barrier nested closer to the surf line than turtles nesting on an open beach. Combined, these results show that turtles face greater reproductive threats when facing barriers, either due to nest inundation (Witherington et al., 2011), or increased predation risk, as suggested at Conklin Island.

Studies of tortuosity as a measure of orientation in freshwater turtles suggest that more tortuous paths indicate random movements in turtles (Caldwell and Nams, 2006). Upon emergence to nest, terrapins orient with the slope of the land upon finding a location to begin digging their nests (Burger, 1977). My findings at Conklin Island suggest that bulkheading causes terrapins to walk less directly in search of a suitable nesting location. Thus, terrapins' nesting success is threatened due to bulkheading at Conklin Island on two levels; predation risk from increased terrestrial travel, and impaired orientation confounding their abilities to find a suitable nesting location.

Aquatic Temporal Measures

The relative measures for time spent by nesting terrapins in the aquatic habitat at each site are very different than those relating to the terrestrial habitat. At Sedge Island there were significantly greater individual and total surfacings by terrapins outside of a

bulkheaded beach compared to the control. In addition, SUR receptions documented nesting females spending more time in the water outside bulkheaded areas as opposed to unblocked beaches. Perhaps terrapins at Sedge Island are using the aquatic habitat near nesting beaches to perceive and assess barriers prior to emergence. There is no indication that these nesting behaviors are occurring at Conklin Island, however, as terrapins were not found to surface more frequently or spend greater amounts of time in the aquatic habitat outside of a bulkheaded beach.

Previous studies used only the terrestrial distance from emergence to oviposition to quantify nesting behavior in terrapins (Burger, 1977). Recent studies suggest the need to study nest site selection from the aquatic habitat (Szerlag-Egger and McRobert, 2007), although none have yet been able to quantify it. Hence, my study is the first to utilize turtle surfacing or acoustic receptions in the aquatic habitat proximal to a nesting beach as proxies for 'time spent nesting' and relative nesting behavior. Measuring this aquatic activity is essential for nesting ecology studies, considering time outside of a nesting beach is time when an individual is not likely foraging, mating or participating in other essential activities. As a result, nesting terrapins spending more time in the aquatic habitat outside of Sedge Island's bulkheaded beaches may exhibit lowered fitness rates because they have lost time towards other important life history activities. In addition, bulkheaded nesting areas contain many anthropogenic threats within their aquatic habitat. Many of these developed areas are homes, recreational docks, or marinas which exhibit higher boat traffic levels and crab pot frequency. Terrapins increasing their time within the aquatic habitat proximal to development are also increasing their risk to these serious survivorship threats.

Site Variation

My study suggests that terrapins at different locations utilize the terrestrial and aquatic habitats differently in response to barriers. Differences in vegetation, geometry, and human activity between Sedge and Conklin Islands' nesting beaches may explain the variation. In response to bulkheading at Sedge Island, terrapins spend more time to nest in the water, not on land. At Conklin Island, however, terrapins are not spending more time in the water before nesting due to bulkheading, and instead travelling significantly greater distances on land. Thus, I hypothesize that bulkheading results in increased energy expenditure by nesting female terrapins, however the habitat where this additional effort takes place is variable by site.

Hayes (1995) found that between nesting sites, topography and vegetation were driving factors for nesting distance in sea turtles, with uneven beach topography cuing digging at one beach, while the constraint of dense vegetation was a driving factor at another. Similarly, terrapins require low density vegetation at their nesting beaches (Burger and Montevecchi, 1975). However, at both of my sites, Conklin and Sedge Islands, nesting terrapins faced relatively equivalent vegetation species and cover (approximately 25-50 cm of *Phragmites sp.*, which they traverse to open nesting habitat of patchy grass and sand mosaic). Accordingly, it is unlikely that variation in terrapins' terrestrial movements between sites is due to vegetative qualities, as was the case for Hayes (1995), although future studies should consider nesting beaches' topographical characteristics. In terms of natural beach variation between Conklin and Sedge Islands, a more probable hypothesis takes into account differences between these islands' geometry. The fact that Conklin Island is long and narrow while Sedge Island is more

wide and round is a likely cause for inter-site modifications in terrapin nesting distance on land.

Variation in human activity on the nesting beaches is another explanation for observed differences in terrapin nesting behavior between sites. Sedge Island has supported an active education center over the past ten years, housing up to thirty young students in the area of the nesting beaches daily. Nesting terrapins have been handled repeatedly over that time period as well. Conklin Island, however, remains comparatively less disturbed. The decision to emerge from the water to nest is not affected by human activity in the freshwater turtle *Chrysemys picta* nor is their nesting habitat selection (Bowen and Janzen, 2008). In this case, turtles nesting near areas of high human activity become habituated to anthropogenic disturbances over long periods of time (Whittaker and Knight, 1998). Thus, terrapins at Sedge Island may be allotting their additional nesting efforts due to bulkheading towards spending more time in the water due to the greater number of visual stimuli (i.e., humans) on land. Females at Conklin Island, on the other hand, may not be as habituated to human impacts, and emerging onto the beach at a quicker rate. They may only realize the impact of bulkheading upon emergence, and subsequently directing their additional nesting exertion to travelling on land, as opposed to dwelling in the water.

Conservation Implications

With the current uncontrolled rate of population growth and subsequent development in shore communities (Kennish, 2001), it is imperative that we consider wildlife behavior to shoreline barriers in estuarine management. My model species, the terrapin, spent significantly more time in the water, and travelled greater distances on

land in order to nest at their preferred nesting beach due to bulkheading. This is important in terms of management, because it supports various observations of human-wildlife interactions within mid-Atlantic estuaries. Telemetry surveys of horseshoe crabs have underscored the importance of understanding the exact temporal and spatial overlap of crab habitat and anthropogenic activities, including bulkheading (Moore and Perrin, 2007). Breeding and nest survival of shorebirds is also negatively affected by human recreation upon beach habitats (Carney and Sydeman, 1999). Models for piping plover habitat availability after sea level rise in Fire Island Sound, NY suggest that only with habitat migration will plover habitat increase over time (Seavey et al., 2011). Shoreline migration under this model is impossible with current shoreline armoring, such as bulkheading, holding back the sea (Scavia et al., 2002). Therefore, bulkheading has severe long-term impacts on estuarine wildlife, as well as causing short-term behavioral changes.

Nesting female turtles utilize the very same sites that humans disturb through development (Gibbons et al., 2001); areas of low vegetation density, open sand, and direct sunlight (Szerlag-Egger and McRobert, 2007). This is why thousands of female terrapins are killed by motor vehicles as they traverse roads adjacent to historic nesting beaches in New Jersey (Wood and Herlands, 1997). Barriers such as roads and bulkheading have led to observations of terrapins using marginal habitats to nest (Roosenburg, 1994), such as backyards and driveways instead of finding new, more suitable nesting sites. This reality should be of particular concern, as it suggests that as human development increases, the likelihood of nest success decreases, incurring significant population declines. Although terrapins at Conklin and Sedge Island alter

some nesting movements by travelling around bulkheading or spending more time in the water, they are not altering their fidelic nesting locations by finding a new, unblocked beach at which to nest – much like the terrapins consistently found along roadways or in coastal backyards. Thus, my results support observations that terrapin's evolutionary nest site fidelity is not adapting based on the anthropogenic changes around them. These results generate both population and community-level ecological concerns.

Therefore, if terrapins are not modifying their fidelic behavior, humans must instead change their shoreline development practices. For sea turtles losing nesting habitat to impending sea level rise, dune rebuilding was emphasized as a technique to reconstruct natural beaches (Mazaris et al., 2009). Indeed, crocodiles have been observed relinquishing disturbed nesting sites in favor of newly created nesting sites (Leslie and Spotila, 2001). For this reason, the abundance and distribution of nesting habitat in mid-Atlantic estuaries needs to become a serious consideration, especially in a now human-dominated ecosystem. Additional nesting habitat should be artificially created, away from sources of mortality, as previously suggested for freshwater turtles (Baldwin et al., 2004). Also, areas of high terrapin nesting activity should be preserved. In Barnegat Bay, the only high frequency nesting beaches remaining are those which are on protected lands (Unpublished surveys 2006-2012). With the onset of global climate change and increased storm surges, the development of new land along estuaries should be strongly reconsidered (Scavia et al., 2002). Because this seems unlikely, the alternative of human development and subsequent bulkheading continuing to increase is highly probable. If this less-advised scenario occurs, individual permitting of bulkheading must be put in place. By allowing land-owners the opportunity to decide how best to protect their

properties from erosion, we allow wildlife to face a more penetrable shoreline.

Bulkheading must not be continuous, and any new development should be mandated to include a wildlife corridor every 500m (at minimum, to decrease visiting wildlife's contact with humans) directed to an artificial nesting habitat.

Over the next 25 years, the ever-increasing human population along estuarine shorelines will create greater demands and pressures on estuarine systems (Kennish, 2002). My study shows that wildlife are not prepared to adapt to rapid loss of habitat, and humans must instead change their practices. Through improved coastal development practices, such as artificial beach growth, local permitting, and living shorelines, terrapins and other estuarine wildlife may withstand human encroachment upon their habitat. By helping wildlife coexist with humans in this way, we can maintain the ecological and economic integrity of our treasured estuaries.

Table 3-1. Nesting terrapin's terrestrial and aquatic responses to bulkheading at Sedge and Conklin Islands in Barnegat Bay, NJ. Values represent means of their representative measure. Values in bold indicate a significant difference ($p < 0.01$) between groups at a site. Superscript labeling indicates significant differences between groups within and between sites.

<i>Terrestrial Measures</i>	CONKLIN					SEEDGE				
	Statistical Test	Experimental	Avoid	Control	<i>P</i>	Experimental	Avoid	Control	Test Value	<i>P</i>
Total Distance (m)	ANOVA	68.12^a	12.58^b	19.40^{bc}	<0.01	44.27 ^{ac}	30.80 ^c	32.30 ^c	0.85	0.28
Net Displacement (m)	ANOVA	25.86^a	10.32^b	17.67^b	<0.01	16.14 ^b	14.80 ^b	16.29 ^b	0.38	0.77
Tortuosity	None	0.53^a	0.11^b	0.06^b	—	0.53 ^a	0.43 ^a	0.37 ^a	—	—
Time on Land (min)	Kruskal Wallis	—	—	—	—	30.44	18.78	17.14	2.24	0.33
<i>Aquatic Measures</i>										
Individual Surfacing 2010	Poisson	1.12 ^a	—	0.61 ^{ab}	-0.19	2.14^a	—	0.50^b	3.20	<0.01
Individual Surfacing 2011	Poisson	1.45 ^a	—	1.64 ^a	-0.19	4.38^a	—	2.81^b	3.20	<0.01
Total Surfacing 2010	Poisson	1.42 ^a	—	0.71 ^a	-1.43	1.82^a	—	0.49^b	6.67	<0.01
Total Surfacing 2011	Poisson	9.47 ^a	—	16.42 ^a	-1.43	33.28^b	—	4.17^c	6.67	<0.01
SUR Presence (%)	Kruskal Wallis	0.03 ^a	—	0.04 ^a	0.52	0.50^b	—	0.24^c	6.63	<0.01

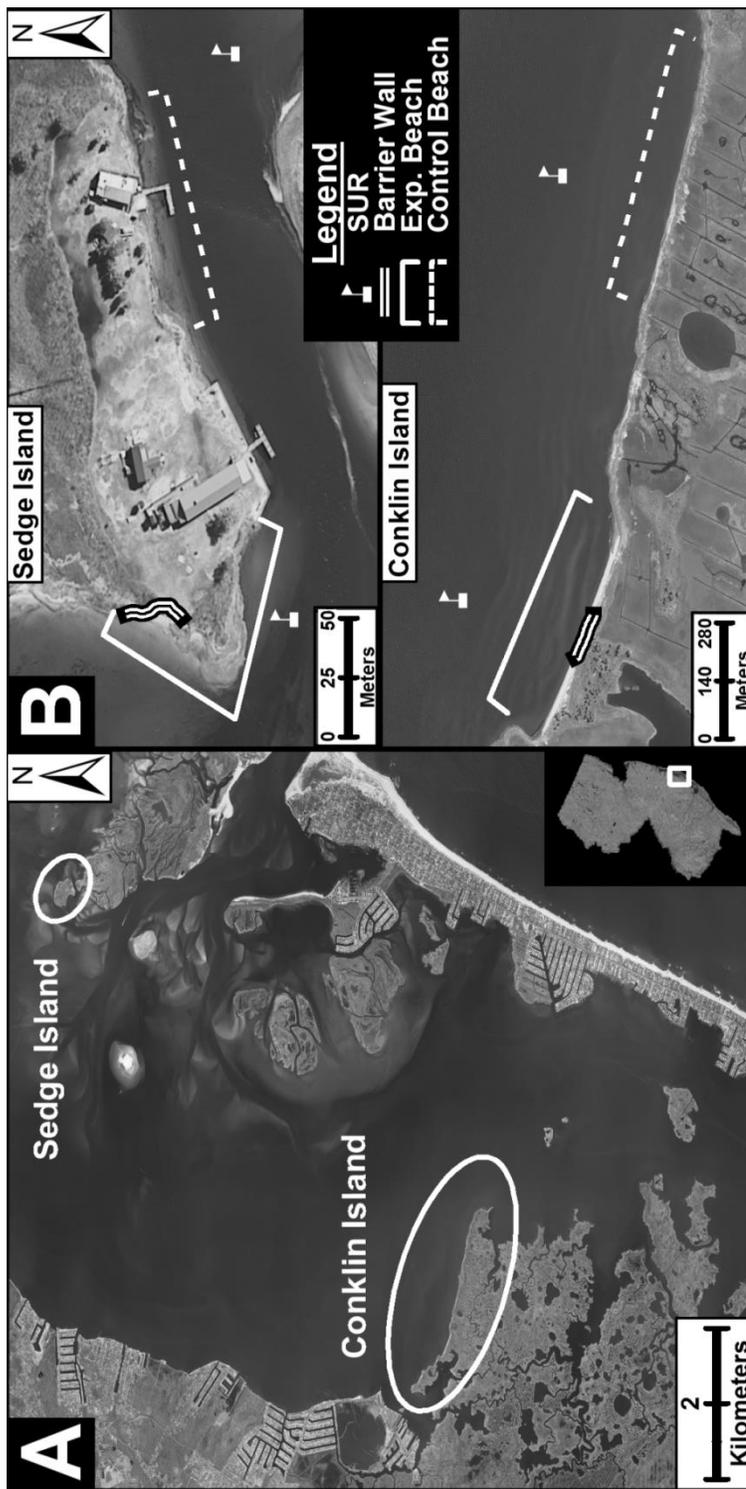


Figure 3-1. Study Site (A) in Barnegat Bay, NJ with terrapin nesting survey sites, and Experimental Design (B) demonstrating beaches of closure (experimental) and remaining as is (control) at both Sedge and Conklin Islands.



Figure 3-2. Yodock bulkheading *in situ* on Conklin Island, Barnegat Bay Estuary.

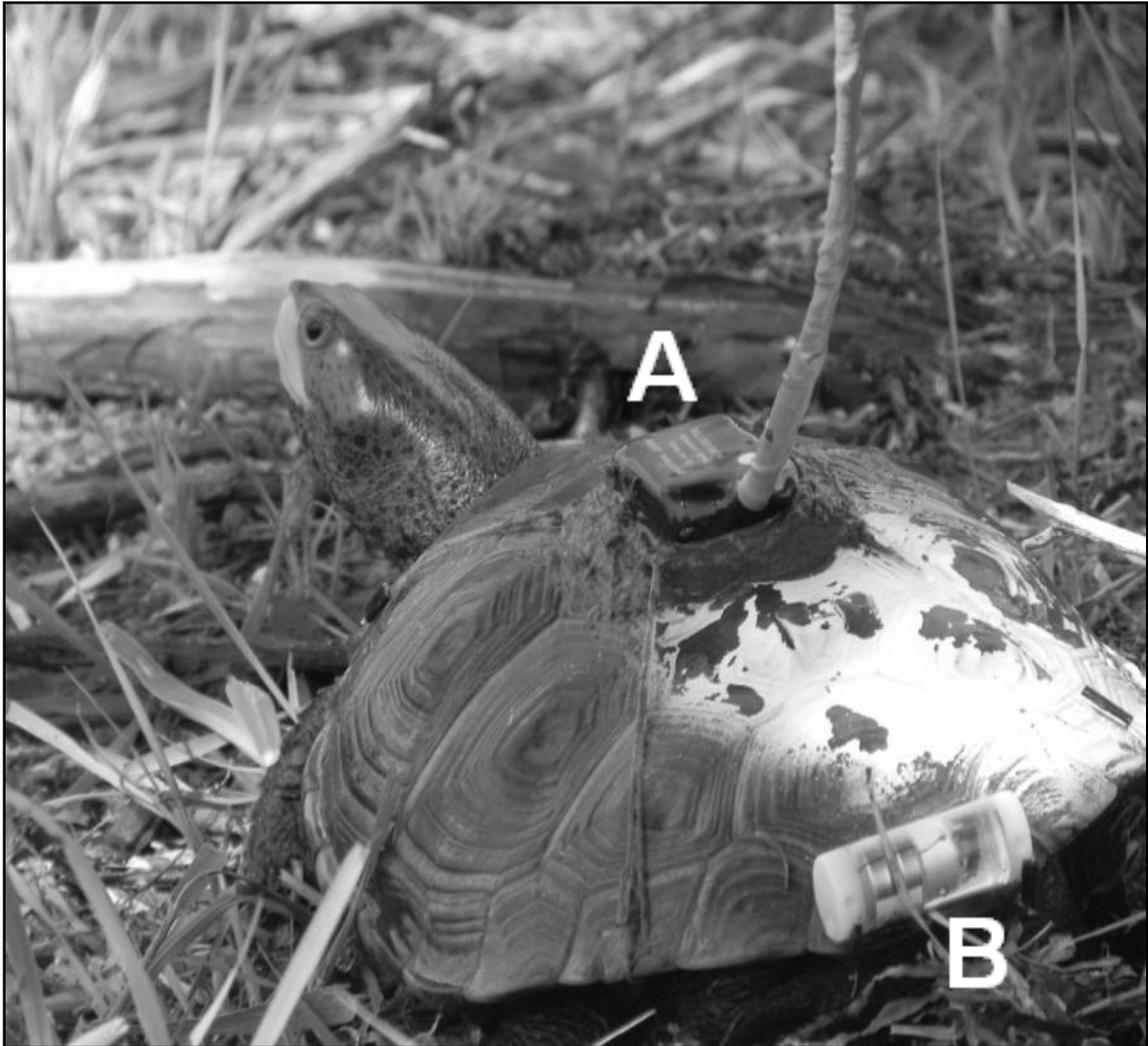


Figure 3-3. Gravid terrapin outfitted for radio (A) and sonic (B) telemetry. Photo courtesy of Alyssa Frediani.

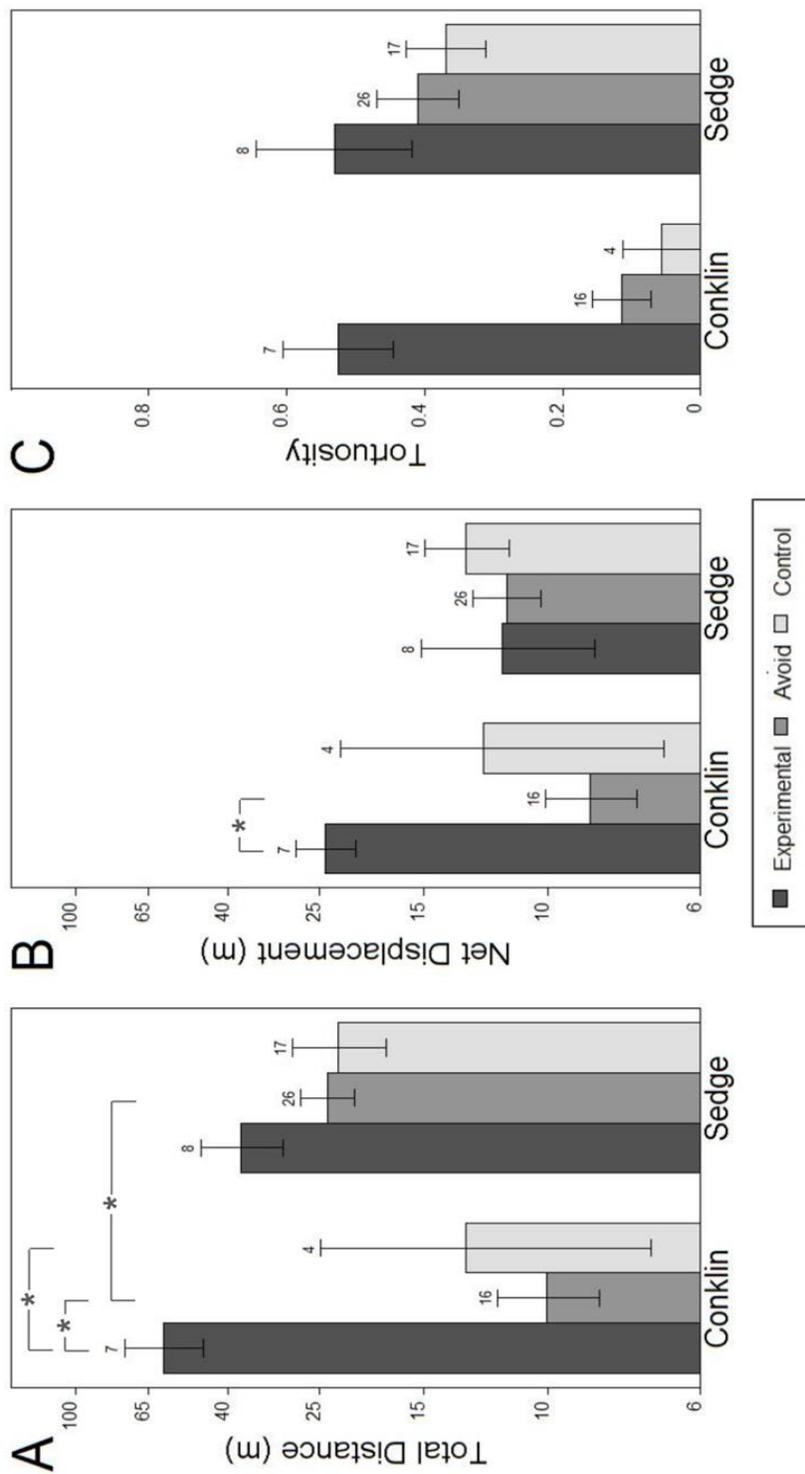


Figure 3-4. Terrestrial measures of Total Distance (A), Net Displacement (B) and Tortuosity (C) of nesting diamondback terrapins in experimental, avoid and control groups on Sedge and Conklin Islands in 2011. Numbers document sample size. Asterisks indicate statistical significance at $p < 0.01$. Bars represent one standard error. A and B are shown on a log axis.

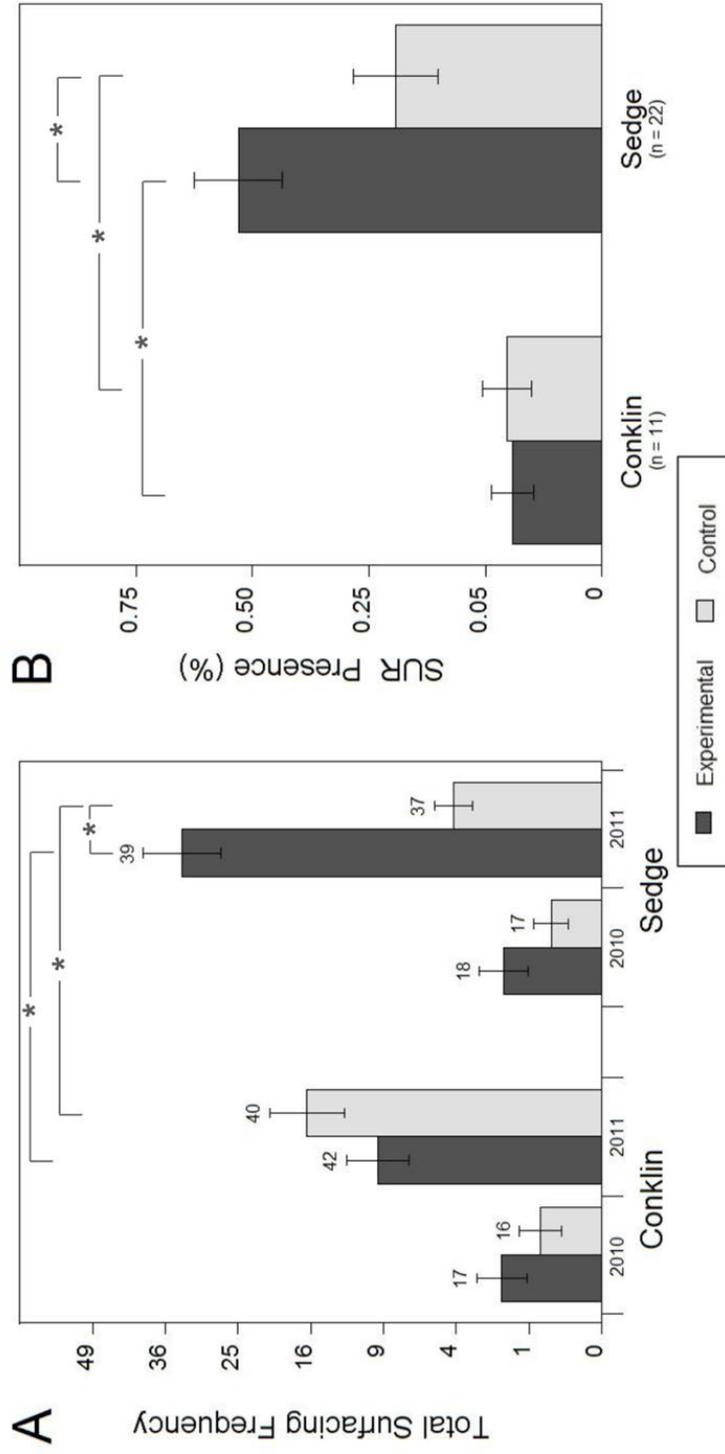


Figure 3-5. Aquatic measures of Total Surfacing Frequency (A) and SUR Presence (B) of nesting diamondback terrapins in the aquatic habitat of experimental and control beaches at Sedge and Conklin Islands in 2010 and 2011. Individual Surfacing Frequency data (not shown) illustrate a similar pattern to Total Surfacing Frequency. For Total Surfacing Frequency, numbers documented sample size (total days surveyed) and data are shown on a square-root axis. SUR Presence data are presented on an ArcSine axis. Asterisks indicate statistical significance at $p < 0.01$. Bars represent one standard error.

CHAPTER 4: THE STRESS RESPONSE OF NESTING DIAMONDBACK TERRAPINS TO BULKHEADING IN BARNEGAT BAY, NJ.

Abstract

Anthropogenic stressors such as habitat loss are a global problem for wildlife. Coastal development has reduced natural habitats in Barnegat Bay, New Jersey, and 36% of this estuary's shoreline has been replaced with hard shoreline erosion barriers such as bulkheading. The diamondback terrapin (*Malaclemys terrapin*) must reach the very same upland habitat that is becoming increasingly barricaded by bulkheading for annual nesting. To determine the effects of bulkheading on this imperiled species' nesting abilities, I measured terrapin adrenocortical response (i.e., stress) to artificial bulkheading by quantifying steroid hormones corticosterone and testosterone post-barrier exposure. I obtained blood samples immediately upon capture from 91 nesting terrapins at both experimentally bulkheaded and adjacent reference beaches. In addition, I exposed 15 individuals to handling stress and bled them at 30 and 60 min following capture to create plasma profiles of acute corticosterone secretion. There were no significant increases in corticosterone or testosterone due to bulkheading, indicating that barriers did not elicit a stress response in nesting terrapins. After handling, terrapin profiles of acute corticosterone increased significantly over 60 min to 8 ng/ml, however hormone secretion in terrapins encountering bulkheading did not approach these peak levels. Testosterone significantly dropped over the course of the reproductive season, while corticosterone levels stayed constant throughout, consistent with other Chelonian species. Nesting females' lack of stress response to bulkheading suggests that terrapins do not physiologically respond to anthropogenic changes in their habitat. Consistent with these

findings, many terrapins are found nesting in shorefront yards and along roadways, apparently oblivious to their surrounding's dangers. The diamondback terrapin's habituation to human activity should encourage wildlife managers to implement access ramps to artificial nesting habitat near bulkheading, knowing that terrapins will utilize these structures without becoming stressed. With the increasing rate of bulkheading construction in Barnegat Bay, and along most shorelines, this study acts as a novel approach to guiding management of the human-wildlife conflict within America's estuaries.

Introduction

It is well known that external perturbations trigger a stress response in vertebrates, taking the form of a glucocorticoid release (Gregory et al., 1996; Valverde et al., 1999; Lance and Rostal, 2002; Davis et al., 2008). In this way, steroid hormones promote an adaptive response that enhances survival in organisms coping with environmental (Wingfield et al., 1998; Jessop, 1999) and anthropogenic (French et al., 2010; Crino et al., 2011) disturbances. In reptiles, the physiological consequences of the neurohormonal stress response to a chronic stressor include compromised immune responses, repressed growth, and disruption of reproductive hormone function (Mahmoud and Licht, 1997; Berger et al., 2005; French et al., 2010). In order to quantify this hormonal cascade and its various effects, endogenous rhythms of the hypothalamo-pituitary-adrenal (HPA) axis must be measured for each specific species of concern (Rostal et al., 2001), as daily cycles of glucocorticoid secretion will confound the basal activity of the HPA in response to a specific stressor (Valverde et al., 1999). Although well documented within sea turtle

literature (Rostal et al., 2001), the reproductive endocrinology of diamondback terrapins (*Malaclemys terrapin*) remains relatively unknown.

The diamondback terrapin is an estuarine turtle found along the Atlantic and Gulf coasts of the United States (Cash et al., 1997). Terrapin populations are in decline throughout the species' range (Gibbons et al., 2001; Harden et al., 2009), due to anthropogenic activities including watercraft and automobile traffic, crab trapping, and the encroachment of shoreline development along estuarine habitats (Cecala et al., 2009). Of particular concern, human development upon terrapin nesting beaches threatens long-term population viability through its direct negative effect upon the reproductive success of this fidelic species (Sheridan et al., 2010). Terrapins emerge onto high-dune habitat for nesting annually, exhibiting very high levels of fidelity to their natal beaches (Burger and Montevecchi, 1975; Butler et al., 2004; Szerlag-Egger and McRobert, 2007; Sheridan et al., 2010). The loss of fidelic nesting beaches and subsequent reproductive consequences is likely stressful to female terrapins as they search for new, potentially less suitable habitats. As shoreline development and subsequent bulkheading (a vertical retaining wall used for erosion prevention) continues at an accelerated rate, the fidelic sites that terrapins, and other estuarine wildlife such as shorebirds and horseshoe crabs, require for reproduction are continuously becoming inaccessible.

Over the past thirty years, Barnegat Bay Estuary, New Jersey, has displayed the highest coastal development rate of any mid-Atlantic estuary, with subsequential bulkheading replacing 36% of natural shorelines (Jivoff, 2007). The consistent form of shoreline hardening in Barnegat Bay, bulkheading poses a serious threat to estuarine wildlife at the individual, population, and community levels (Kennish, 2002). While the

negative ecological impacts upon intertidal marsh species are well studied (Able et al., 1998; Weis et al., 1998; Seitz et al., 2006; Long et al., 2011), few studies have investigated the impacts of bulkheading on wildlife moving between aquatic and terrestrial habitats, and none have measured species' stress responses.

The purpose of this study was to determine if bulkheading elicits significant stress responses in reproductive diamondback terrapins at fideic nesting beaches.

Corticosterone (CORT) levels were used as a primary indicator of stress, with testosterone (T) used to indicate any complementary alterations to reproductive hormonal secretions. Considering CORT and T secretion levels are unknown in reproductive terrapins, I measured: a) acute CORT secretion during handling stress, and b) CORT and T hormonal fluctuations throughout the nesting season to establish baseline hormone values. I determined changes in CORT and T due to terrapin responses to beach conditions at two nesting sites. Terrapin responses included making contact with barriers, avoiding barriers at experimental beaches, or not encountering bulkheading at control beaches. Experimental results of CORT and T from each response scenario were corrected to seasonal reproductive hormone fluctuations, and then compared to handling stress levels to determine if terrapins reached elevated CORT secretion due to barrier exposure. I hypothesized that nesting terrapins interacting with bulkheading would display a higher stress response than terrapins that avoided bulkheading when attempting to nest or encountered an unobstructed beach.

Materials and Methods

Site Selection and Experimental Manipulation

My study sites included two terrapin nesting areas in Barnegat Bay, New Jersey, U.S.A (39°47'N, 74°9'W): Conklin Island, within the Edwin B. Forsythe National Wildlife Refuge, and Sedge Island, one kilometer west of Island Beach State Park (Figure 4-1). I selected these sites based on their historically high levels of nesting activity. Wnek (2010) reports a mean of 90 individual female terrapins arriving to nest annually at Sedge Island, with an estimated population size of 430 ± 23 total individuals. Nest depredation surveys at Conklin Island indicate over 100 nests per kilometer (Unpublished surveys, 2006-2012).

At both Sedge and Conklin Islands, I determined the two beaches with the highest nesting activity (Wnek, 2010; Unpublished surveys, 2006-2012). At these two beaches, previous surveys allowed us to identify the locations of greatest nesting terrapin emergence frequency. I blocked the beach with maximum nesting activity with Yodock™ plastic construction barriers (The Yodock Wall Company INC., Model 2001M (Metropolitan), 182 x 45 x 81 cm) central to this location of high nesting terrapin emergence. Barriers were set up parallel to the vegetation line at the high water mark. My modeled bulkhead wall consisted of approximately 25% (Conklin 67.7m, Sedge 20.1m) of the total 'experimental' beach length at each site. An adjacent 'control' beach remained unobstructed.

Blood Collection

From June through July 2011, I conducted daily surveys simultaneously at experimental and control beaches on Sedge and Conklin Islands for six hours each day.

Investigators sat in an inconspicuous location among *Phragmites australis* (common reed) while monitoring emergences of nesting terrapins. Upon emergence, investigators recorded female terrapins' path along the beach and then collected them after either one minute of attempted oviposition, or after completed oviposition. Heparinized blood samples (2 ml) were collected within 5 minutes of capture through subcarapacial venipuncture using a 23-gauge needle. Fifteen terrapins were randomly selected for successive bleeding at 30 and 60 minutes post-capture to measure acute corticosterone response to handling. These individuals were placed in 19-liter plastic buckets between sampling intervals. All terrapins were re-released into the nearest water where they were originally captured. I stored blood samples on ice for 3-6 hours prior to being centrifuged for five minutes at 3300 RPM (Fisher Scientific Centrifuge Model 228 Benchtop). Plasma was stored at 20° for four months prior to transfer in liquid nitrogen for transport to Statesboro, Georgia for assay.

Hormone Assays

I conducted enzyme immunoassays (EIA) to determine T and CORT concentrations from each terrapin plasma sample (T: n = 83, CORT: n = 87). Hormones were extracted from thawed plasma samples using ether. I performed EIAs on extracted hormone samples following manufacturer's instructions (Cayman Chemical Company, Ann Arbor, Michigan). Thirty samples were combined to form a pooled control, which was diluted from 2:1 to 0.125:1 after being reconstituted in EIA Buffer. The intra-assay coefficient of variation (CV) for T assays was 11.82%, and inter-assay CV was 14.39%. CORT assays had an intra-assay CV of 8.86% and inter-assay CV of 10.8%.

Statistical Analyses

All data were tested for normality and homogeneity of variances before completing statistical analyses. To normalize residuals, hormone levels were log-transformed prior to analyses. All tests were completed using R version 2.15.0 (The R Foundation for Statistical Computing).

I completed two preliminary analyses as hormonal controls for my data. First, I determined if there was significant increase in CORT between samples collected at 1 to 5 minutes after capture due to handling stress. Here, I grouped all samples based on time from capture to venipuncture, and tested between time groups using a one-way analysis of variance (ANOVA). Second, considering some terrapins were collected prior to oviposition, while others were captured after having completed nesting, I completed a one-way ANOVA to determine if there were significant differences in T and CORT levels between individuals before and after nesting.

Two analyses were completed to indicate baseline T and CORT hormone profiles – one to determine a profile of acute CORT secretion, and another to show seasonal variation in both reproductive hormones. First, to indicate peak CORT secretion in the species, I produced an acute CORT response curve of terrapins exposed to handling stress. Here, I determined if CORT levels from samples collected from immediate venipuncture (0 min), after 30 minutes, or after 60 minutes were significantly different using a one-way ANOVA and post-hoc Tukey's range test. Second, I created an independent regression model for both CORT and T concentrations relative to Julian date. Each hormone's regression factor was incorporated into every subsequent analysis to control for any effect of reproductive state over sampling.

To determine the effect of bulkheading upon terrapin adrenocortical responsiveness between and within Sedge and Conklin I grouped terrapins into three treatment groups: 1) Terrapins making contact with and/or walking around experimental bulkheading were considered 'experimental,' 2) Terrapins emerging onto the experimental beach without making contact and/or walking around bulkheading were deemed 'avoid,' and 3) Terrapins emerging onto the control beach were called 'control.' T and CORT levels were compared separately between treatments and sites using a two-way ANOVA.

Results

Effects of Acute Stressor and Reproductive Status on CORT and T

I found no significant effect of sampling time on CORT levels ($F = 2.6$, $p = 0.11$, $n = 79$), indicating that all samples collected within five minutes of capture were not biased by handling stress. In addition, there was no significant difference in CORT between terrapins bled before and after oviposition ($F = 0.21$, $p = 0.65$, $n = 85$). However there was a significant difference in T between pre and post-oviposition terrapins, suggesting that females bled before oviposition had higher T levels than those having completed oviposition ($F = 11.59$, $p = 0.001$, $n = 83$, Figure 4-2). Thus, the point at which bleeding occurred in relation to oviposition was considered in all subsequent testosterone analyses.

Hormone Profiles

My acute response curve showed a significant increase in CORT over time, approaching 7.8 ng/ml at its peak after 60 minutes ($F = 7.91$, $p = 0.001$, $n = 15$, Figure 4-

3). Terrapin stress was significantly higher from initial bleeding to thirty minutes afterwards ($p = 0.02$) as well as sixty minutes afterwards ($p = 0.001$). There was no significant increase in CORT from thirty to sixty minutes due to handling stress ($p = 0.56$).

My regression model for CORT did not suggest any correlation between Julian date and hormone concentration ($t = -0.15$, $p = 0.88$, $n = 85$), indicating that there is no change in CORT over the nesting season (6 June – 12 July). Conversely, my regression model for T showed a negative correlation between Julian date and hormone concentration ($t = -10.02$, $p < 0.001$, $n = 83$), signifying a decrease in T in reproductive female terrapins over the course of the nesting season (Figure 4-4).

Effects of Bulkheading on CORT and T

I found no significant difference in CORT levels between terrapins at Sedge and Conklin Islands ($F = 0.25$, $p = 0.62$, $n = 84$). Terrapins in experimental, avoid, and control groups showed no significant variation in CORT at either site. ($F = 2.0$, $p = 0.14$, Figure 4-5).

Terrapin T levels were not significantly different between Sedge and Conklin Islands ($F = 3.37$, $p = 0.07$, $n = 86$), nor were they different between experimental, avoid, and control group terrapins at each site ($F = 1.71$, $p = 0.18$). Both seasonality (i.e., Julian date of nesting, $F = 16.00$, $p < 0.001$) and reproductive status (i.e., pre or post oviposition, $F = 114.00$, $p < 0.001$) had significant effects on T levels.

Discussion

Reproductive diamondback terrapins exposed to bulkheading do not elicit a stress response while nesting. In addition to the valuable conservation implications of these data, my study also provides a novel addition to reproductive endocrinology profiles for wild Chelonian species.

Based on my handling stress response curves, future studies may now be confident in their hormone sampling techniques over certain periods of time. If a reproductive female terrapin is bled within five minutes after capture, researchers can be assured that the sample's CORT levels are not biased by handling stress. Considering that free-living slider turtles, *Trachemys scripta*, show no increase in CORT after 10 minutes of handling (Cash et al., 1997), it is important to determine the acute stress-response threshold for sampling at a species-specific level. My acute sampling after 30 and 60 minutes showed a significant increase over time, estimating a peak CORT response of 8 ng/ml. Sea turtle studies for reproductive females report CORT levels of approximately 5 ng/ml in loggerhead turtles, *Caretta caretta* (Gregory et al., 1996), 7 ng/ml in the olive ridley, *Lepidochelys olivacea* (Valverde et al., 1999), and 2 ng/ml in green turtles, *Chelonia mydas* (Aguirre et al., 1995) after 60 minutes. I only considered the terrapin's acute stress response for the purposes of this study because this was the most likely reaction elicited by bulkheading. However, future studies should continue serial bleeding for longer than 60 minutes to determine the effects of chronic stress on hormone levels. Indeed, CORT in *C. caretta* does not peak until after 180 minutes of serial sampling (Gregory et al., 1996).

My study is the first to report reproductive endocrinology in diamondback terrapins during the nesting season. First, no significant differences were found in CORT levels between females bled before and after oviposition, varying only from 2.1 to 1.9 ng/ml. This suggests that CORT does not fluctuate during oviposition – a potentially taxing reproductive activity. Second, CORT levels remained stable over the course of the nesting season, similar to those of leatherback turtles, *Dermochelys coriacea* (Rostal et al., 2001), and *L. olivacea* (Valverde et al., 1999). As a reproductive tradeoff, this suppressed adrenocortical stress response may be an adaptive trait helping females complete the nesting process despite the stresses inherent to coming on land (Rostal et al., 2001).

Terrapin T levels varied widely during reproductive activity. Terrapins bled prior to oviposition, at 473.0 pg/ml, have higher T secretion than those bled after oviposition, having a mean T value of 310.8 pg/ml. In addition, T was significantly higher at the beginning of the nesting cycle, and gradually decreased as the season continued. *Dermochelys coriacea* also show elevated T levels at the beginning of their nesting cycle, when their ovaries are mature (Rostal et al., 2001). As ovary size decreases, T will begin to drop, eventually reaching baseline levels at the end of the nesting season (Rostal et al., 2001). Single-clutching freshwater turtles, such as yellow-blotched map turtles, *Graptemys flavimaculata*, have fluctuating T levels throughout their nesting season (Shelby et al., 2000). On average, diamondback terrapins will lay two clutches per nesting season in Barnegat Bay, New Jersey (Wnek, 2010). Thus, the steady T decline in female terrapins over the nesting season matches that of multi-clutching sea turtles, such as *C. mydas*, *C. caretta*, and *L. kempfi* (Licht et al., 1979; Wibbels et al.,

1990; Rostal et al., 1997). Indeed, McPherson et al. (1982), saw the same steady decline in T levels in multiclutched freshwater stinkpot turtles, *Sternotherus odoratus*. This suggests that testosterone cycling similarities among Chelonians root in the number of clutches produced by the Chelonian species, not necessarily the two species' inter-relatedness.

Future stress-related studies in reproductive female terrapins will not have to monitor T in addition to CORT levels, as I found no correlation between CORT and T release over the nesting season. Thus, CORT secretion was not linked to reproductive hormone release in terrapins. This is an insightful discovery for the field of Chelonian endocrinology, considering it matches findings in *D. coriacea* (Rostal et al., 2001), but is contrary to results on reproductive hormone cycling for *C. caretta* (Whittier et al., 1997). Thus, defining the relationship between reproductive and stress related steroid hormones still requires species-specific analyses, and cannot be assumed across taxa.

Nesting female diamondback terrapins did not elicit a significant stress response when encountering bulkheading at their fidelic nesting beaches. Similarly, CORT levels in Galápagos marine iguanas exposed to tourists never reached their expected acute stress levels (Romero and Wikelski, 2002), although the tourists caused a chronic stress response. Here, the importance of a chronic versus acute stressor must be emphasized, as French et al. (2010) found increased stress-induced CORT levels in the same species due to acute human interactions, although iguanas regularly exposed to tourism showed suppressed CORT levels. In terms of habitat modification, eastern hellbenders, *Cryptobranchus alleganiensis*, show no significant increase in CORT when living in a heavily impacted versus higher quality streams (Hopkins and DuRant, 2011), a chronic

response. Nestling white-crowned sparrows, *Zonotrichia leucophrys oriantha*, on the other hand, had increased CORT levels at close proximity to roads than nestlings at a further distance from a chronic highway stressor (Crino et al., 2011). In addition, after having their natal pond drained by humans, *T. scripta* showed acutely elevated CORT levels simultaneous to their emigration to an intact pond habitat (Cash and Holberton, 2005).

It is clear that wildlife responds differently to acute versus chronic forms of anthropogenic impacts within their habitats. In fact, in organisms experiencing chronic stress acute CORT secretion can be suppressed, causing a deceptive null response (Berger et al., 2005). Determining if bulkheading elicits a chronic CORT response in diamondback terrapins would require knowing the duration of human development exposure for each individual terrapin prior to my experiment, as well as repeated sampling post-bulkheading exposure. Although the nesting terrapins in my study showed no acute CORT response to bulkheading, I am not able to determine at this time if bulkheading instead elicits a chronic response.

General Implications

With human development and wildlife habitat continuing to merge and overlap, maintaining both parties' safety has become a global conservation concern (Gore et al., 2008). Simple barriers and easement structures such as drift fences (Aresco, 2005), or culverts (Dodd et al., 2004) have been used to deter wildlife from particularly dangerous areas of human development, such as roadway. For example, over four thousand female terrapins had been killed by motor vehicles adjacent to nesting habitats in Stone Harbor, NJ from 1989-1995 (Wood and Herlands, 1997), and recently installed

drift fencing has helped reduce terrapin mortality (R. Wood, personal communication). Drift fences have also been used for over 65 years to study the reproductive biology and behavior of aquatic turtles (Gibbons, 1970). The logistical limitations and species-specific sampling biases have been well documented for this collection technique (Butler et al., 2004). However, despite the perpetuation of drift fences being used for wildlife sampling, it was not known if collected animals elicit a stress response that could affect reproductive ability or bias other measures. My results are important because they show that when turtles encounter barriers such as drift fences, they are not stressed, even when reproductive. Therefore, this may validate a research and conservation technique that has become standard in turtle ecology as well as wildlife mitigation.

Conservation Implications

From a conservation perspective, it is encouraging to report that bulkheading does not trigger a stress response - a result which would otherwise suggest a profoundly negative affect on the overall reproductive abilities of terrapins. Considering the vertebrate stress system plays a central part in an organism's ability to adapt to their changing environment (Valverde et al., 1999), my physiological results are consistent with other terrapin researchers' observations of terrapins exhibiting no behavioral modifications in relation to anthropogenic activities (Harrison, 2010; Lester, 2012).

Based on my observations during this study, terrapins will nest despite bulkheading. Consistently, terrapins are found nesting in people's backyards along New Jersey's shorelines (Winters, *personal observation*). Indeed, females may be 'attracted' to human disturbed sites for nesting, as they provide minimal vegetation, optimal space, and direct sunlight (Szerlag-Egger and McRobert, 2007). If terrapins were stressed by the

threats caused by humans, it is not likely that they would frequent high-impact, potentially dangerous areas in this way. Instead, the multiple anthropogenic threats facing terrapins while nesting, including bulkheading, are not causing a stress response large enough for them to react.

The terrapins' lack of a stress response to bulkheading yields valuable insight towards future shoreline development design. Wildlife and land managers should be encouraged that nesting terrapins do not elevate stress hormones when confronted with bulkheading, as it provides opportunity to enhance disturbed terrapin nesting habitat. Based on my results, terrapins may be able to use ramps or other bulkhead modifications to breach long stretches of bulkheading, without increasing their physiological stress. Indeed, many of the sites where terrapins access human backyards around bulkhead are characterized by nearby boat ramps which they walk up (Winters, *personal observation*). Conservation managers should capitalize on this behavior by improving bulkheaded habitats through ramp installation, and enhancing upland areas near these ramps to reduce risks to nesting females and maximize nest success.

My study shows that terrapins, in particular, are not physiologically prepared to adapt to rapid habitat loss, and humans should manage their shoreline development accordingly. Through appropriate shoreline augmentation and enforcement of more sustainable development practices, terrapins and other estuarine wildlife may be protected from anthropogenic threats. Over the next 25 years, the ever-increasing human population along estuarine shorelines will create greater demands and pressures on estuarine systems (Kennish, 2002). Thus, maintaining the ecological and economic integrity of our treasured Atlantic estuaries requires immediate action.

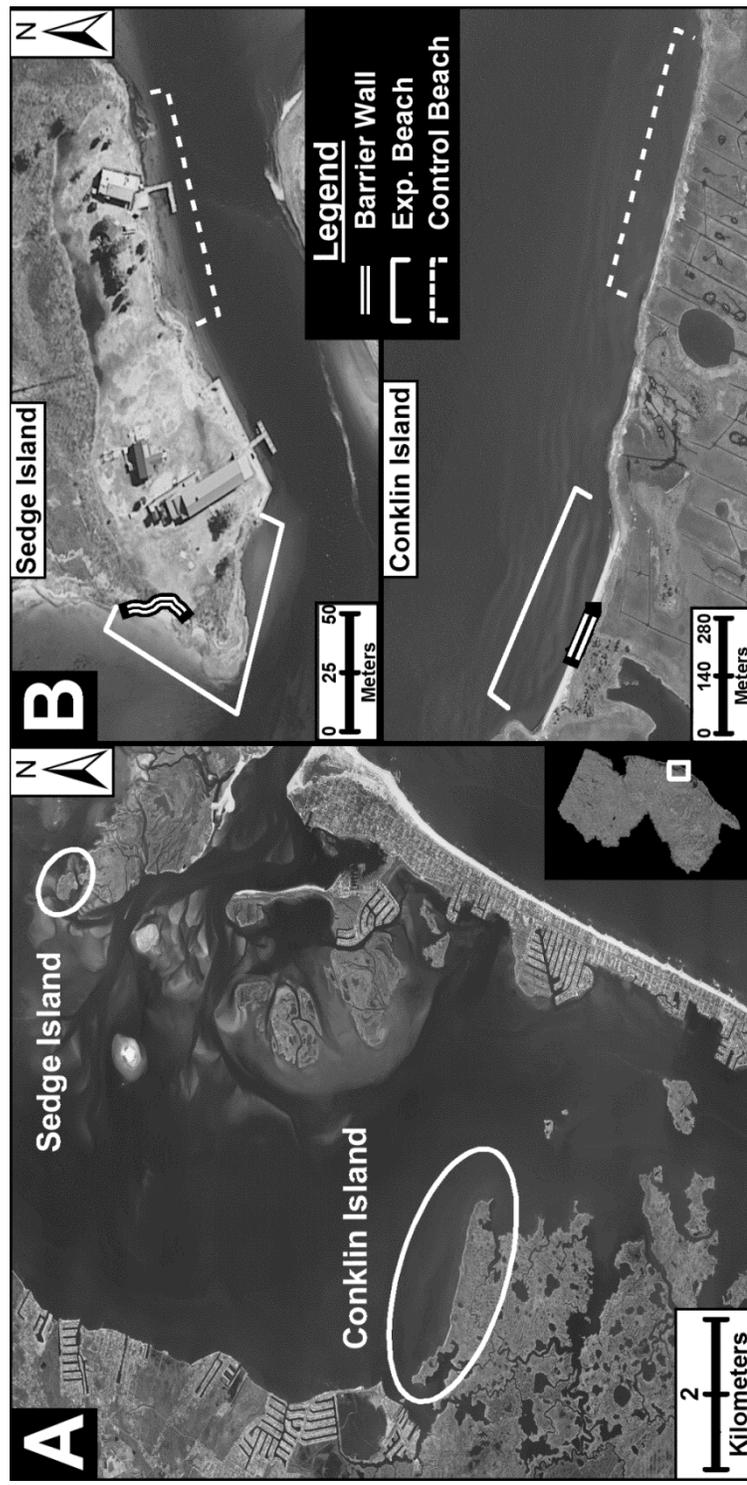


Figure 4-1. Study Location (A) in Barnegat Bay, NJ with terrapin nesting survey sites, and Experimental Design (B) demonstrating beaches of closure (experimental) and remaining as is (control) at both Sedge and Conklin Islands.

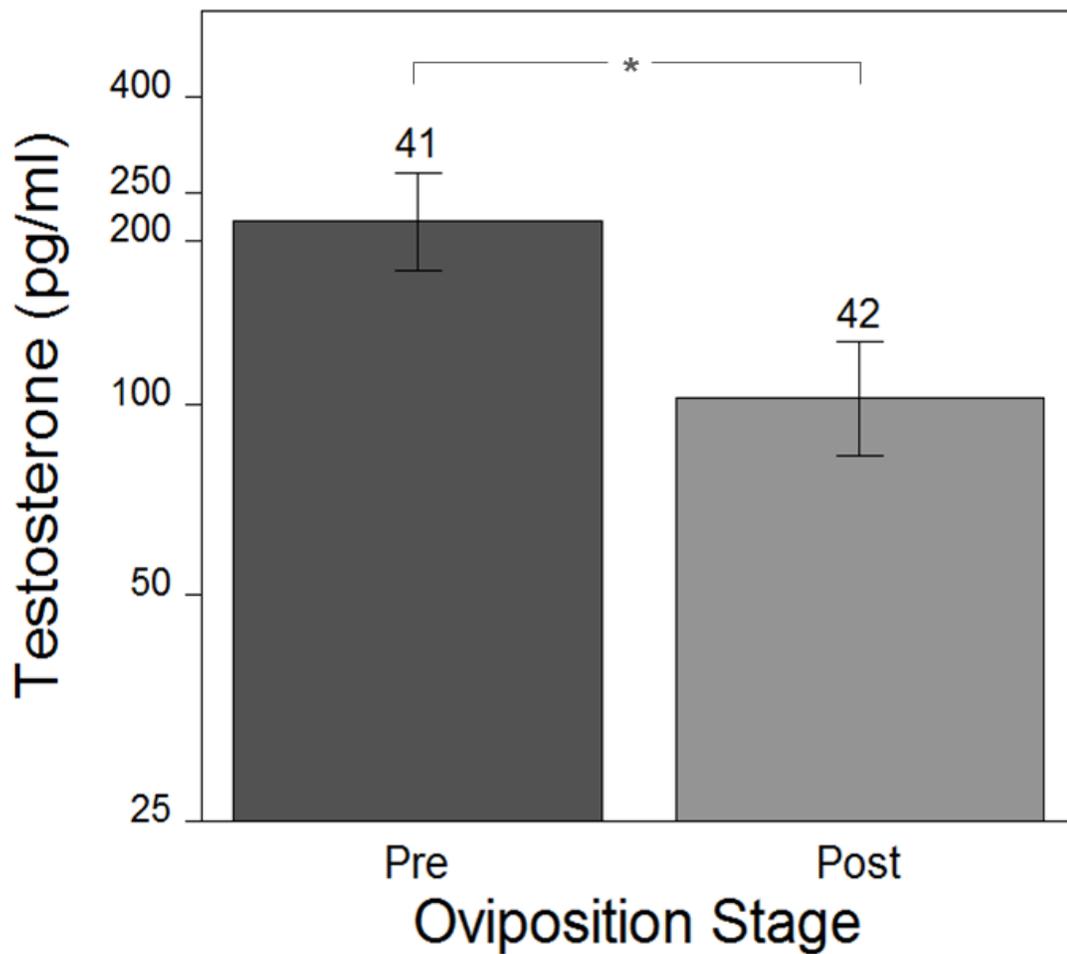


Figure 4-2. Testosterone levels of reproductive female terrapins bled before (Pre) were significantly greater than those bled after (Post) oviposition. Vertical axis is log transformed. Numbers document sample size. Asterisks indicate statistical significance at $p < 0.05$. Bars represent standard error.

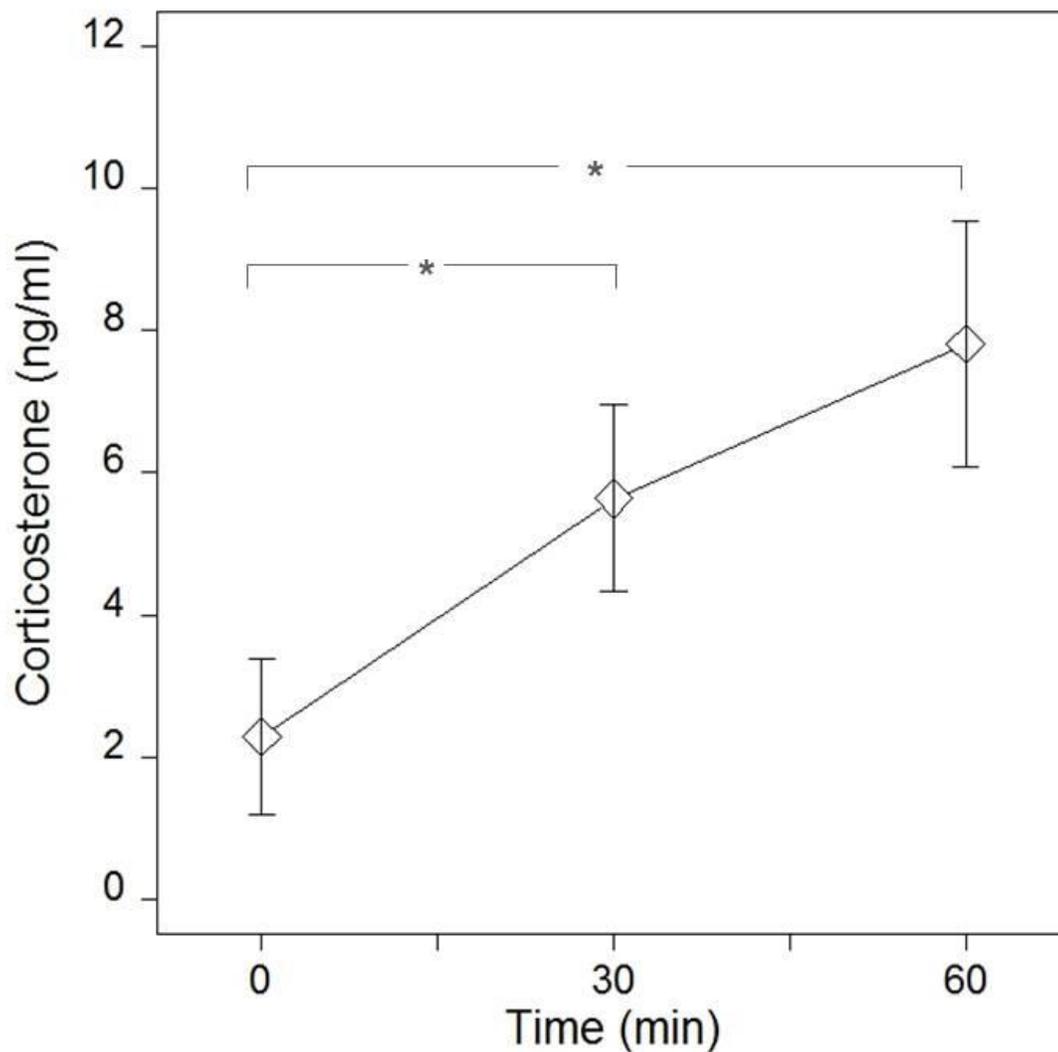


Figure 4-3. Acute CORT levels of reproductive female diamondback terrapins bled initially (0 min) and after 30 and 60 minutes show a steady increase in hormone release over time due to handling stress. N = 15. Asterisks indicate statistical significance at $p < 0.05$. Bars represent standard error.

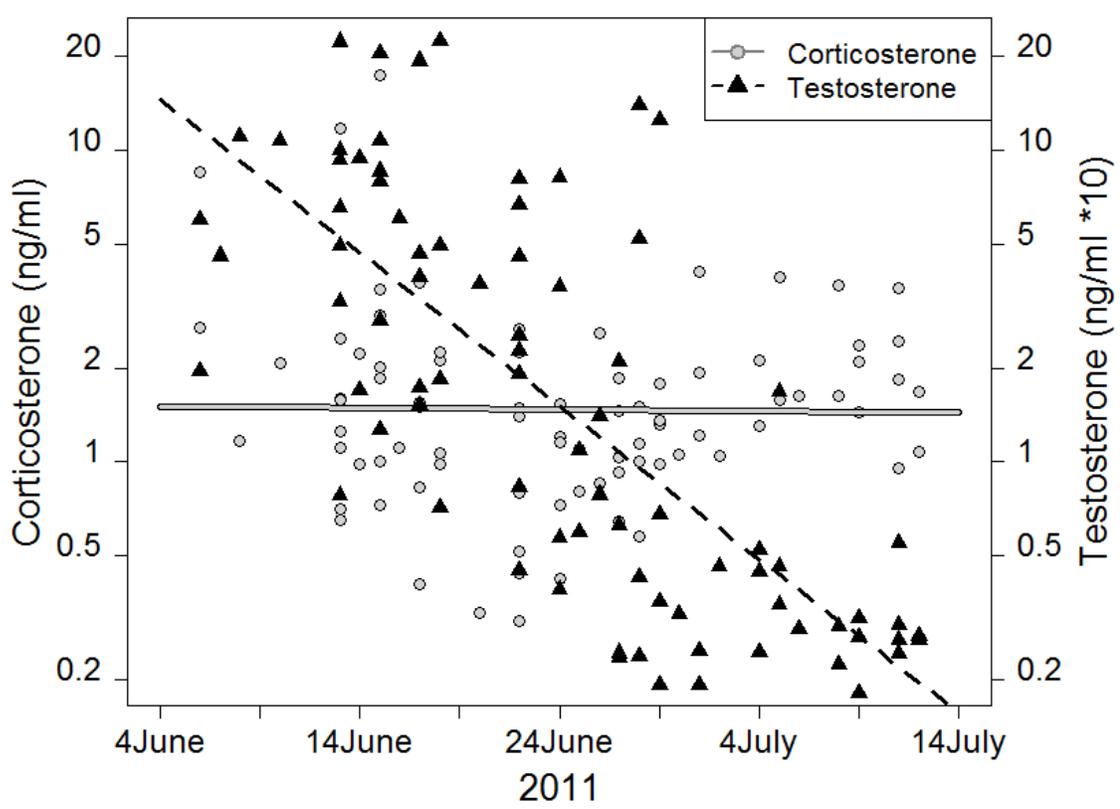


Figure 4-4. Seasonal correlations of CORT and T over the diamondback terrapin nesting season show no change in CORT over time while T steadily decreases. T and CORT were not correlated. Hormone curve axes are log transformed.

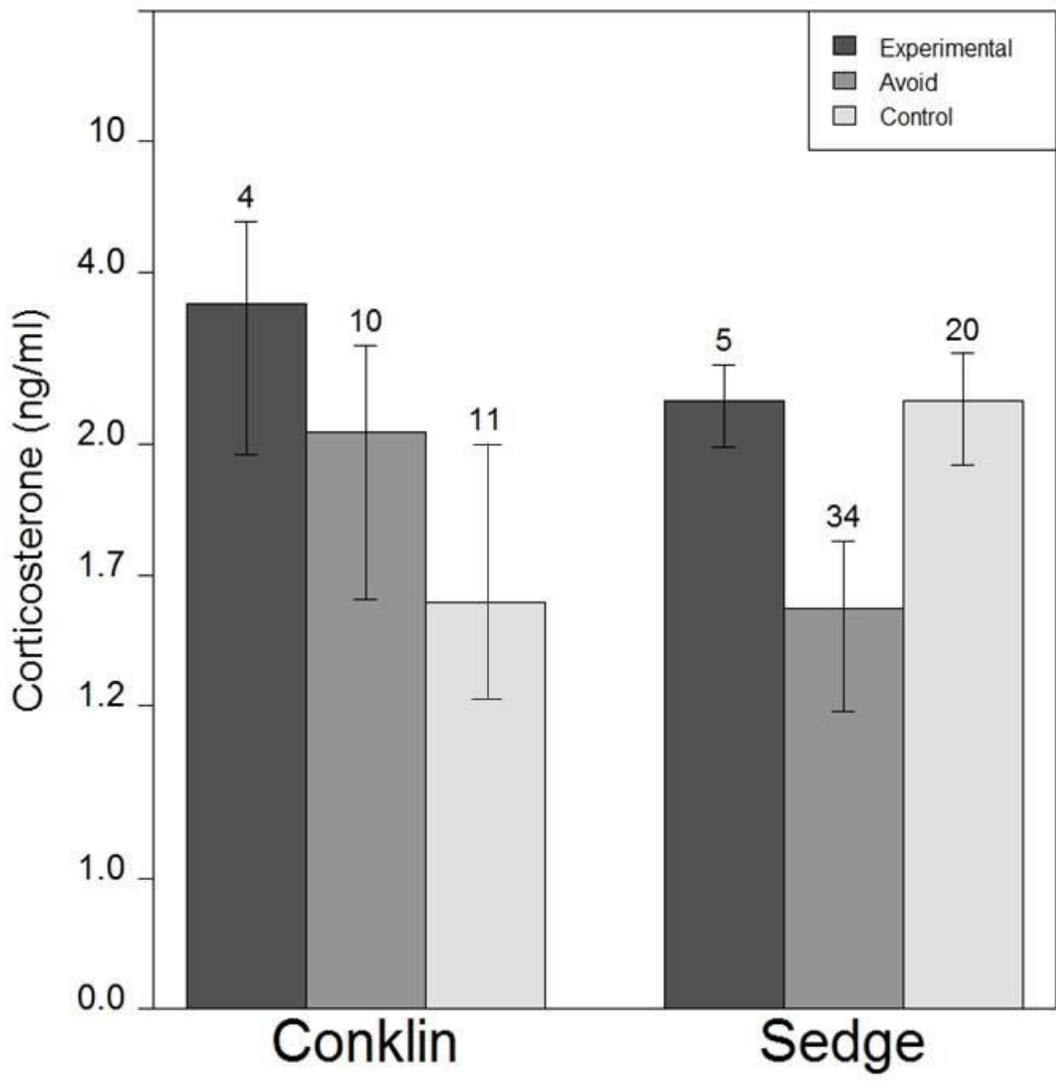


Figure 4-5. CORT levels of nesting diamondback terrapins exposed to bulkheading indicate no significant difference in stress response between experimental, avoid, and control groups. Data are represented on a log axis. Numbers document sample size. Bars represent standard error. $p < 0.05$.

CHAPTER 5: THESIS SYNOPSIS AND CONSERVATION IMPLICATIONS

Dissertation Summary

Environmental and Anthropogenic Nesting Triggers

Previous surveys of diamondback terrapin nesting behavior have found the highest frequency of individuals emerging to nest mid-day, with moderate cloud cover, during mild days at warm temperatures exclusively at high tide. In Chapter 2, probability of terrapin emergence was calculated in relation to these environmental factors, pinpointing more precise values that can be used to predict terrapin nesting emergence. Terrapins were most probable to emerge for nesting around 13:30, at water temperatures near 26°C, air temperatures near 27.5°C, and during outgoing tide. There was no significant relationship between cloud cover or wind speed with terrapin emergence. During these optimal conditions, the probability of terrapins emerging to nest was not affected by the presence of motorized boats, personal water crafts (PWCs), humans walking or swimming, kayaks, or any combination of these four activities. The environmental factors influencing terrapin nesting should be used by wildlife managers as guides for restricting threatening human activities proximal to nesting.

Changes in Aquatic and Terrestrial Nesting Movements to Bulkheading

In Chapter 3, spatial and temporal movements of nesting terrapins - both on land and in the water - were compared between experimentally bulkheaded versus open beaches. Terrapins encountering bulkheading did not travel significantly greater distances, or spend more time on land in order to nest at Sedge Island. Instead, SUR receptions and surfacing frequency models indicate that Sedge females spend more time in the aquatic habitat outside of bulkheaded nesting beaches. At Conklin Island, nesting

terrapins travelled significantly further on land, with less oriented paths due to bulkheading. In the water, however, terrapins were not found to surface more frequently or spend greater amounts of time in the aquatic habitat outside of a bulkheaded beach at Conklin. Overall, terrapins at different locations utilize the terrestrial and aquatic habitats differently in response to nesting barriers. This suggests that bulkheading results in increased energy expenditure by nesting female terrapins, however the habitat where this additional effort takes place is variable by site. Therefore, if terrapins are not modifying their fidelic behavior, humans must instead change their shoreline development practices. Areas of high terrapin nesting activity should be preserved, individual permitting of bulkheading must be put in place, and additional nesting habitat should be artificially created, away from sources of terrapin mortality.

Stress Response to Bulkheading and Reproductive Endocrinology of Nesting Females

Corticosterone (CORT) and testosterone (T) secretion levels for nesting females reported in Chapter 5 are the first reproductive endocrinology profiles for wild diamondback terrapins. CORT did not fluctuate during oviposition – a potentially taxing reproductive activity – nor were CORT levels altered over the course of the nesting season. However, diamondback terrapin T levels varied widely during reproductive activity. Terrapins bled prior to oviposition had higher T secretion than those bled after oviposition. Also, T was significantly higher at the beginning of the nesting cycle, and gradually decreased as the season continued, suggesting a correlation between T secretion and follicle development. There was no correlation between CORT and T secretions over the nesting season. Thus, CORT secretion was not linked to reproductive hormone release in diamondback terrapins. Reproductive diamondback terrapins exposed to

bulkheading did not elicit a stress response while nesting. Generally, these results validate drift fences being used for decades to study the reproductive biology and behavior of reptile species as well as for wildlife mitigation, as these structures are not creating a stress bias on experimental data. Conservation managers should capitalize on this behavior by improving bulkheaded habitats through ramp installation, and enhancing upland areas near these ramps to reduce risks to nesting females and maximize reproductive success.

Synthesis

Diamondback terrapins lack behavioral and physiological responses to anthropogenic stressors, such as bulkheading at their nesting beaches. Natal philopatry and attachment to particular environmental conditions appear to be well-rooted factors in terrapin nesting behavior, blinding terrapins to the actual threats caused by humans. Bulkheading does not deter nesting diamondback terrapins from emerging to nest at their fidelic beach. Bulkheading does, however, alter the distance that these females travel on land, and the amount of time they spend in the water before emerging. Increasing time in both terrestrial and aquatic nesting habitats elevates the probability of terrapin exposure to anthropogenic threats such as motorized boats and crab pots in the water, as well as vehicular traffic and predators on land. Further increasing their risk, diamondback terrapins do not alter the timing of their emergence to nest due to the presence of any of these anthropogenic factors, instead relying exclusively on environmental cues. Bulkheading not eliciting a stress response from diamondback terrapins offers further support for the species' apparent detachment from human-induced nesting threats.

Other studies have shown barriers such as roads and bulkheading lead to terrapins using marginal habitats to nest (Roosenburg, 1994), such as backyards and driveways instead of finding new, more suitable nesting sites. This reality should be of particular concern, as it suggests that as human development increases, the likelihood of nest success decreases, incurring significant population declines. Although terrapins in Barnegat Bay alter some nesting movements by travelling around bulkheading or spending more time in the water, they are not altering their fidelic nesting behaviors by finding a new, unblocked beach at which to nest – much like the terrapins consistently found along roadways or in coastal backyards. Thus, my results support observations that terrapin's evolutionary nest site fidelity is not adapting in response to the anthropogenic changes around them. These results generate both population- and community-level ecological concerns. Because diamondback terrapins do not display behavioral or physiological modifications when nesting around bulkheading, humans must instead alter their coastal development practices.

Conservation and Management Recommendations

With the current uncontrolled rate of population growth and subsequent development in terrapin habitats (Kennish, 2001), it is imperative that we consider terrapin response to shoreline barriers in estuarine management. The abundance and distribution of nesting habitat in mid-Atlantic estuaries needs to become a serious consideration, especially in a human-dominated ecosystem. With the onset of global climate change and increased storm surges, the development of new land along estuaries should be strongly reconsidered (Scavia et al., 2002). Because this seems unlikely, the

alternative of human development and subsequent bulkheading continuing to increase is highly probable. If this less-advised scenario occurs, recommendations for incorporating diamondback terrapin nesting behavior in sustainable coastal development and recreational activities are as follows:

1. Areas of high terrapin nesting activity should be preserved and maintained. In Barnegat Bay, the only natural high frequency nesting beaches remaining are those which are on protected lands (Unpublished surveys 2006-2012).
2. Wildlife managers must temporally limit human activities at high fidelity nesting beaches from June through mid-July. Considering motorized boats and PWCs do not alter terrapin nesting emergence, these activities, in particular, should be restricted to areas beyond 1 kilometer of fidelic terrapin nesting beaches in Barnegat Bay. This will sufficiently protect the large number of reproductively valuable female terrapins dwelling in these beaches' aquatic habitats during nesting season.
3. For the mandates described in numbers 2 and 3, subsequent enforcement by local, state, and federal rangers is paramount.
4. Nesting terrapins are able to use ramps or other bulkhead modifications to breach long stretches of bulkheading without increasing their physiological stress. Conservation managers should capitalize on this behavior by improving bulkheaded habitats through ramp installation, and enhancing upland areas near these ramps to reduce risks to nesting females and maximize nest success.

5. Additional nesting habitat should be artificially created, away from sources of mortality. Resources for these beaches should be plentiful, as one-year aged dredge soil is a suitable substrate for terrapin nesting (Wnek et al., 2013).
6. If coastal habitat is approved for development, human structures – most importantly, bulkheading – must not be continuous. Any new development should be mandated to include a wildlife corridor every 500m (at minimum, to decrease visiting wildlife's contact with humans) directed to an artificial nesting habitat.

With loss of estuarine biodiversity accelerated by human population growth along many of America's estuaries, it is critical that coastal restoration and wildlife protection are simultaneously governed in order to maintain ecosystem services (Lotze et al., 2006). Rapid human population growth along estuarine shorelines will create greater demands and pressures on estuarine systems over the next 25 years (Kennish, 2002). My study shows that wildlife may not adapt to this rapid loss of natural habitat. Humans must improve coastal development practices in order to successfully protect terrapins and other estuarine wildlife. This is the only means by which we can maintain the ecological and economic integrity of our treasured estuaries – in New Jersey, the Atlantic coastline, and worldwide.

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B.S., Biodiversity & Conservation Biology, Minor in Dance Cedar Crest College, Allentown, PA	2008

PROFESSIONAL EXPERIENCE

Research Director. Princeton/Earthwatch Field Expedition	2012 – 2013
Teaching Assistant. Freshman Biology, Drexel University	2008 – 2013
Research Staff Coordinator. Diamondback Terrapin Project, Drexel	2011
Employee. Diamondback Terrapin Project, Drexel	2008 – 2010
Freshman Research Director. Cigliano Lab, Cedar Crest College	2008
Mentor. Science Majors Actively Recruited for Teaching, NSF	2006 – 2007
Intern. Education and Conservation Depts., The Philadelphia Zoo	2007
Researcher. Queen Conch Population Survey, Turneffe Atoll, Belize	2007
Stranding Intern. The Marine Mammal Center, Sausalito, CA	2006

ACCOLADES, AWARDS AND HONORS

Teaching:

Drexel Graduate Studies' Highly Commended Teaching Excellence Award	2013
Drexel Graduate Studies' Higher Education Advocate Travel Award	2013
Drexel Graduate Studies' Teaching Assistant of the Year Award Nominee	2012
Alternate for the Philopatric Education Organization (P.E.O) Scholar Award	2012
Drexel Graduate Studies' Teaching Assistant of the Year Award Nominee	2010

Research:

Best Graduate Student Poster Presentation in Biological and Biomedical Research at Drexel University's All College Research Day	2012
2nd Place, Graduate Research Poster Presentation at Drexel University's College of Arts and Sciences Research Day	2012
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SELECT PUBLICATIONS AND ABSTRACTS

Winters, J.M., J. R. Spotila, E.A. Standora, and H. W. Avery. (6 Sept 2012). Between the Bay and a Hard Place: The effect of bulkheading on diamondback terrapin nesting in Barnegat Bay, NJ. International Congress of Zoology. Haifa, Israel.

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